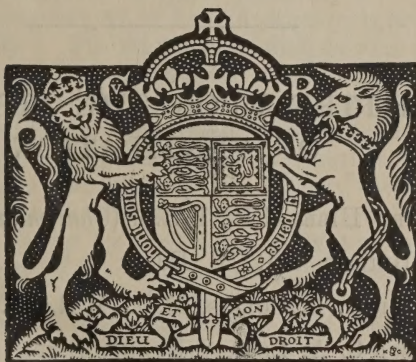


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MEDICAL RESEARCH COUNCIL

METHODS OF INVESTIGATING VENTILATION AND ITS EFFECTS

By H. M. VERNON and Others



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INTRODUCTION

THE present report by Dr. H. M. Vernon and others carries one step further an inquiry initiated by the Medical Research Council into the principles of ventilation, the previous results of which have been published in the *Science of Ventilation and Open-Air Treatment* by Leonard Hill, and in the *Kata-thermometer in Studies of Body Heat and Efficiency*.¹

In these reports it has been shown that the ill-effects of bad ventilation do not result from the chemical impurity of the air, but from want of adequate cooling of the body and evaporation from it.

The successful ventilation of rooms, schools, or factories therefore depends primarily on both the temperature and the movement of the air (though the air should at the same time be kept free from dust and microbic infection), and to indicate these conditions the kata-thermometer was introduced, as an instrument which enables the 'cooling power' of the air, depending as it does on both temperature and movement, to be measured in a simple way. Subsequently, standard cooling powers indicative of the conditions required, according to the nature of occupation, were formulated.

The kata-thermometer was described by its inventor, Leonard Hill, as 'an instrument designed primarily for the measurement of its own rate of cooling when its temperature approximates to that of the human body'. The standard cooling powers set up by him were obtained by empirical graduation of the instrument in conditions of temperature, humidity, and air movement which general opinion accepts as comfortable and fresh. Nevertheless, the mistake has often been made of assuming that in regard to rate of cooling the kata-thermometer can be compared directly with the clothed human body. As is pointed out in the present Report, the fallacy of such an assumption is shown by consideration of the relative surface area and cubic content of the small kata-thermometer bulb and of the big masses of the body, and of the sheltering effect of clothing as indicated by the fact that, as shown by Leonard Hill, the cooling of the kata-thermometer clothed in a wool finger-stall was increased by fanning only 46 per cent. when that of the naked kata-thermometer was increased 146 per cent. Moreover, the body differs from the kata-thermometer in the power to vary its surface conditions and rate of heat-loss by more or less flushing the cutaneous blood-vessels and more or less bringing into action the sweat glands. When the skin is covered with visible perspiration, the wet kata-thermometer is the more comparable, but this no less requires empirical graduation. Under ordinary conditions, the body is not comparable with either the wet or the dry kata-thermometer but with something between the two. Even taking into account these reservations, however,

¹ Medical Research Council, Special Report Series, Nos. 32, 52, and 73.

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the value of the kata-thermometer as an index of ventilation remains much greater than that of the wet- and dry-bulb thermometer, because the latter take no account of air movement, which has the most potent cooling effect on the skin.

The present Report consists of four parts. Part I contains descriptions of two new instruments designed by Dr. Vernon and Mr. J. J. Manley for the measurement of variations (*a*) in the velocity, and (*b*) in the temperature of air currents. For the former purpose a new form of hot-wire anemometer was constructed and was shown to be very sensitive to changes of air velocity, whilst little influenced by changes in air temperature. For the study of changes in temperature, a suitable thermopile was devised, which was found to be unaffected by changes in velocity. The combined use of these two instruments has enabled further light to be thrown on the relative importance of temperature and air movement in ventilation.

In Part II the results of a further calibration of the kata-thermometer are given. It is shown that the kata 'factor', hitherto assumed to be a constant for any individual instrument, is not in fact constant but varies with the temperature. The necessary corrections that have been determined over a wide range will enable the low-air velocities found in ordinary rooms to be measured with far greater accuracy.

Concurrently with these observations, work has recently been carried out in other countries on the calibration of the kata-thermometer. During the last year in Germany the formulae for the dry and wet kata-thermometer have been reinvestigated by Dr. Paul Weiss¹ in the Charlottenburg Institute by means of a wind tunnel, with the result that close agreement with the English observers has been attained in respect of the dry kata-formula, while a new modified formula has been evolved for the wet kata.

Weiss in his experimental observations used both a small tube (apparently not more than two or three times the length of the kata-thermometer bulb in diameter, although the exact dimensions are not given by him), and also a wind tunnel 80 cm. in diameter in the Charlottenburg Institute. It has been found by the Medical Research Council workers that a small tube is inadmissible for such observations, and there is no indication as to which observations were made by Weiss in the small and which in the large tubes. An investigation of the wet kata-thermometer in the large wind tunnel at the National Institute for Medical Research is now in progress, and Weiss's formula will be tested, together with the most important part of his work, which is the suggestion that in the case of the wet kata-thermometer the total amount of heat in the surrounding atmosphere (calculated from the specific heat and latent heat of the observed mixture of air and water vapour corresponding to a unit of dry air) plays an analogous part to that of the dry-bulb temperature for the dry kata-thermometer. Also, in Japan, a book upon the subject is being published by one of the research workers in the Ministry of Labour.

Part III consists of an investigation carried out by Dr. Vernon and Mr. T. Bedford (assisted by Mr. C. G. Warner) with the object of

¹ *Arch. f. Hyg.* 96, Heft 1, 1925.

finding how far the objective indications of the kata-thermometer correspond with actual sensations of comfort.

Experience shows that at a temperature of 65° F., with average humidity and very little air movement, a person used to confinement indoors may do sedentary work when dressed in ordinary clothing, may rid himself of the heat produced in his body, and remain comfortable although with a slight feeling of stuffiness and tendency to mental inertia. To one used to open-air life confinement in such a room would feel oppressive, whilst on the other hand one transported from tropical climate would feel these conditions to be chilly. Acclimatization then makes a great difference to the feelings. As was shown by Argyll Campbell and Leonard Hill, the basal metabolism or rate of production of body heat in the resting state is brought to a lower level in the man habituated to life in the tropics, and to a higher level in the man who is used to open-air life and exposure to cold. The ratio of one to the other may be as considerable as one to two. As the mean temperature of the air gradually rises and the mean cooling power falls, on passage from winter to summer, each of us undergoes a gradual adaptation, and at the same time puts on thinner clothes, and thus comes to experience comfort at a temperature several degrees higher, and a cooling power considerably lower, than that observed in winter. In a previous investigation Dr. Vernon found that he was acclimatized by exposure to high temperatures for about three hours at a time, on alternate days for a month, so that the maximum wet-bulb temperature endured by him without rapid rise of body temperature increased no less than 6° F., while his pulse and respiration rate became much less affected than at first; the loss of sweat at the same time increased.

In order to graduate the kata-thermometer empirically, Dr. Vernon and his fellow observers recorded their 'sensations of air movement' systematically before each determination of cooling power in factories according to an agreed scale, passing in seven intermediate stages from 'very stagnant' to 'very fresh'. The results show the importance of regarding cooling power in relation to comfort as a variable depending on acclimatization, and not as a fixed quantity. They conclude in fact that the cooling power of 6, which Leonard Hill has adduced as the minimum requirement for workers engaged in sedentary occupations, holds for an air temperature of about 64° to 67° F., but that in summer weather a cooling power of 5 would be quite reasonable, whilst in winter it might rise to 7 or more.

The effects of oscillations in air movement and temperature also were explored by means of the specially designed instruments already mentioned. It was found that whilst the sensation of air movement was apparently increased by increasing the oscillations of air velocity, no clear proof was obtained of its increase by oscillations of temperature.

In Part IV Dr. Vernon has studied the rate of cooling of the human body, naked and clothed, after being warmed up by previous exercise, and has in this way thrown further light on the relative importance of air temperature, clothing, and air movements. The results tend to show that in order to induce an actual cooling of men engaged in hot and heavy work, it is of most importance to reduce

the temperature, and of next importance to reduce the clothing, whilst a small increase of velocity has little effect.

It may here be stated that observations at high temperatures (made in the new wind tunnel recently set up in the National Institute for Medical Research) show that velocity can have a very great effect on the warmly clad man, when it is sufficient to drive air through, and so ventilate, the clothing. By means of wind sufficient thus to evaporate sweat from the clothed body, men can be kept much more cool and comfortable, but, losing more sweat, they should drink more, and, to avoid excessive elimination of potassium from the body by sweat and the cramps which that may cause, they should drink a suitable salt solution instead of pure water, as Haldane and Moss have recently urged.

The present Report appears to the Council to contain useful contributions to further knowledge of the requirements of good ventilation, a subject which on account of the many factors involved calls for special study under natural as well as controlled conditions.

The relations between physical environment and the physiological requirements of the normal human body have within recent years received ever-increasing attention, not only in this country, but also abroad and especially in the United States and Germany. In particular, the part played by good ventilation in the well-being of the community is now definitely recognized. In the industrial field it has been shown to lead to increased comfort, efficiency, and production in occupations involving hot and heavy work, and there is reason to believe that it may be an important factor in reducing phthisis and other communicable diseases in occupations where the workers are closely aggregated.

MEDICAL RESEARCH COUNCIL,
15 York Buildings, Adelphi,
London, W.C. 2.

December 8, 1925.

METHODS OF INVESTIGATING VENTILATION AND ITS EFFECTS

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PART I. THE MEASUREMENT OF VARIATIONS IN THE VELOCITY AND TEMPERATURE OF AIR CURRENTS

By H. M. VERNON, M.D., Investigator to the Industrial Fatigue
Research Board, and J. J. MANLEY, M.A., Fellow of Magdalen
College, Oxford.

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1. INTRODUCTION.

It is generally considered that the adequate ventilation of factories and other buildings depends more on the maintenance of a reasonable degree of air movement than on the chemical purity of the air, as shown by carbon dioxide estimations. The kata-thermometer, which is generally employed for measuring the air velocity, takes about a minute to cool through its prescribed range, so it gives us information only about the average velocity, and tells us nothing about the rapid oscillations of air movement which can be demonstrated qualitatively by means of smoke tests and light air vanes. In order to measure such oscillations, we have designed a portable 'hot-wire' anemometer. It was shown by Ser (1888) that the convection loss from a heated wire is proportional to the square root of the velocity of the air current moving against it, and several investigators have suggested the possibility of utilizing this fact for the estimation of wind velocities. Kennelly (1909) determined the current required to keep a small copper wire at a given temperature, as measured by its resistance. He employed wind velocities varying from 2 to 20 metres per second (4.5-45 miles per hour). Macgregor-Morris (1912) used platinum wires which were heated 43° or 71° C. above the air temperature, whilst King (1914) heated his platinum wires to about $1,000^{\circ}$ C. All these investigators kept the temperature of their hot wire constant by appropriately varying the current, though Morris made a few observations in which a constant voltage was employed.

2. THE NEW APPARATUS FOR MEASURING VELOCITY.

Morris used a simple Wheatstone bridge, one arm of which consisted of a wire having a high temperature coefficient, and the alternate arm of a manganin wire. Our apparatus was similar, but in our bridge we substituted twin auxiliary coils of silk-covered

'Eureka' wire for the slide wire. They were wound side by side on a small bobbin and covered with a velvet jacket (cf. Fig. 1). The galvanometer shunt, the variable resistance used in the battery circuit for controlling the strength of the current, and the adjustable resistance required for balancing that of the hot wire, were wound spirally in grooves cut upon three cylinders of vulcanite fibre. Each cylinder (which was 30 mm. wide and 66 mm. in diameter) was mounted axially upon a massive brass screw working in a brass pillar. The grooves upon the cylinders and the threads of the screws were given a pitch of 2 mm. Contact with any part of a given spiral resistance was made through a gold bead which was soldered to a fixed vertical spring, whilst the second contact was obtained through the screw to which one end of the wire was fixed, and its brass support. As the gold bead is non-oxidizable and softer than the wire upon which it presses, the several resistances remain practically unchanged by use. The adjustable standard resistance, and also that in the battery circuit, were of No. 26 'Eureka' wire, each consisting of 12 or 14 turns and offering a total resistance of about 8 ohms. The spiral used in the galvanometer shunt consisted of 13 turns of No. 20 manganin wire. Its resistance was approximately 2 ohms. The strength of the current sent into the bridge was shown by a small ammeter placed in the battery circuit. In every case the current used was 0.5 amp., the current in the hot wire being approximately 0.33 amp.

The hot-wire portion of our apparatus, or 'detector', was of special construction. This was necessitated by the fact that in workrooms the air currents move not only horizontally, but to no inconsiderable extent in a vertical direction. This is owing to warm air rising from the hot-water pipes, &c., at floor level, and cold air descending from skylights and windows. Three platinum wires, each 17 mm. in length and 0.08 mm. in diameter, were soldered on to thick brass wire supports in three planes at right angles, and these supports were mounted on an ebonite ring of 53 mm. internal diameter (cf. Fig. 2). Consequently the effects of air streams, striking the fine wires at any angle whatsoever, attained a maximum value. The resistance of the three wires was about 1 ohm, and the current was sent through all three, though the apparatus was so designed that it could be sent through one or two only, if desired. The detector was mounted on a stand, so that it could easily be adjusted to the required height. It was usually placed on a bench at the head level of the operatives and six feet or more distant from the rest of the apparatus.

The galvanometer was a Paul unipivot dead-beat instrument, of 9.5 ohms resistance. The current was supplied by a two-volt accumulator. The shunt connected with the galvanometer diverted all but 2 per cent. of the current, this arrangement giving the most convenient sensitivity. The galvanometer appeared to respond instantaneously to any change of air current, but an exact record of its movements could be obtained only by a photographic method. This would have proved almost impossible in practice, as the instrument was required in an exceedingly portable form, for use in all sorts of places in factories. Hence the method adopted was for an observer to read

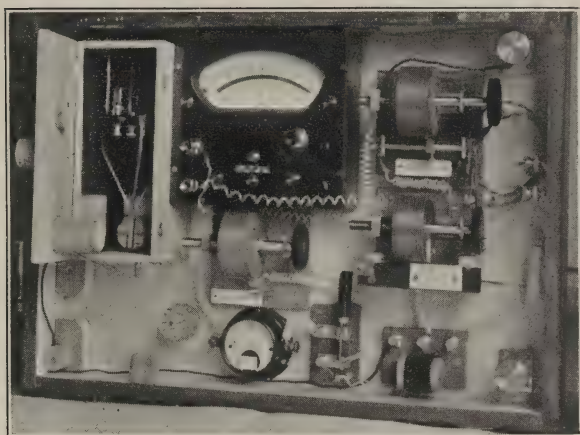


FIG. 1. Apparatus in case.

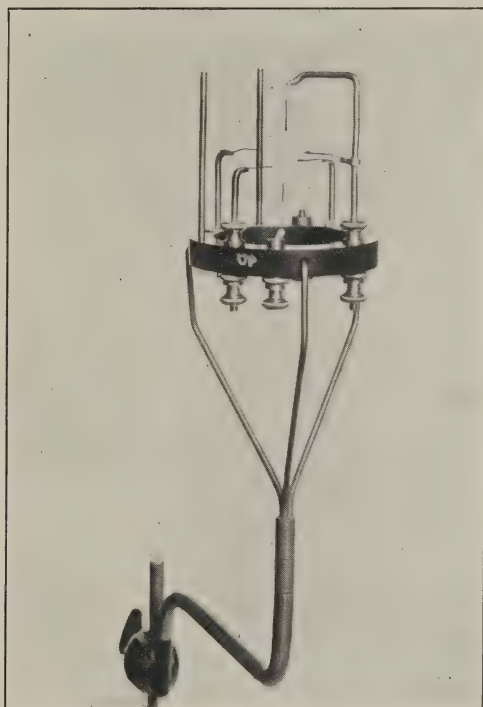


FIG. 2. The hot-wire detector.

off the galvanometer deflexion at intervals of 2 or $2\frac{1}{2}$ secs. as indicated by the ticks of a metronome. As the series of observations was usually continued for five minutes, 150 or 120 readings were obtained. The whole apparatus, except the accumulator, packed into a case $21 \times 15 \times 6$ inches, and weighed 23 lb. The case was provided with levelling screws, as it often had to be placed on benches having irregular surfaces.

Resistance measurements showed that with 0.5 amp. current, the temperature of the hot wires was about 134° C. when kept in nearly still air at 15° C.

When using the apparatus, the detector was first covered by an inverted cylindrical tin ($5 \times 3\frac{1}{4}$ inches). The mouth of the tin was packed with cotton-wool so as to prevent access of air currents. When the circuit was completed, the needle of the galvanometer attained a constant position in about 15 seconds, and as it did not show any further movement in the course of the next few minutes, it follows that the heat given off by the hot wires was not sufficient to raise the temperature of the air in the tin appreciably. It was found that the change of galvanometer reading produced by a rise or fall of temperature was 4.5 scale divisions for each $^{\circ}$ C. As the air temperature might rise or fall appreciably during the five minutes for which the observations lasted, we always noted the scale reading (with the detector covered up) at the finish as well as at the start, and took a mean, but the readings seldom differed by more than two divisions. It was found to be convenient to re-number the galvanometer scale from left to right (120 divisions), and we always adjusted the galvanometer to a starting-point of ten divisions.

3. THE CALIBRATION OF THE HOT-WIRE ANEMOMETER.

The calibration of the anemometer gave a great deal of trouble. We made a complete series of observations by the 'revolving arm' method (cf. Part II of this Report), in which the detector was screwed to one end of the arm, and electric contact with the galvanometer circuit was made by means of wires dipping into two concentric annular mercury pools at the base of the supporting pillar of the arm. Fresh mercury was used daily, but the slight increase of resistance due to the contamination of the mercury or to polarization effects reduced the galvanometer deflexion appreciably, and rendered the calibrations valueless. Hence a second series was made by comparing the anemometer against a kata-thermometer in a small wind tunnel. This tunnel was 7 ft. in length and $17\frac{1}{2}$ inches in diameter. It was made by sticking together several layers of brown paper, and supporting the paper by fixing it within four wooden hoops. A 15-inch electric fan was placed just within one end of the tunnel, and as it induced too great air velocities for our purpose, it was covered, in front, with two layers of cheese cloth. In addition, the current driving the fan was passed through a slide rheostat, so that it could be graduated exactly.

The velocity of the air currents passing through a small wind tunnel constructed in this fashion is not even, being greater at the periphery of the tunnel than at its centre. Observations made with the

detector showed that it was not always equal at equal distances from the side, so special precautions were taken to nullify the effects of this source of error. The kata and the detector were placed at opposite sides of the tunnel in such positions that the kata bulb and the hot wires were just four inches from the wall. Two cooling observations were made (the deflexion of the galvanometer being read off at the same time as the kata was cooling), and then, after transposing the instruments, two more observations were made, and a mean taken of the two sets. Frequently observations with a vane anemometer were made in addition (cf. Part II). The instruments

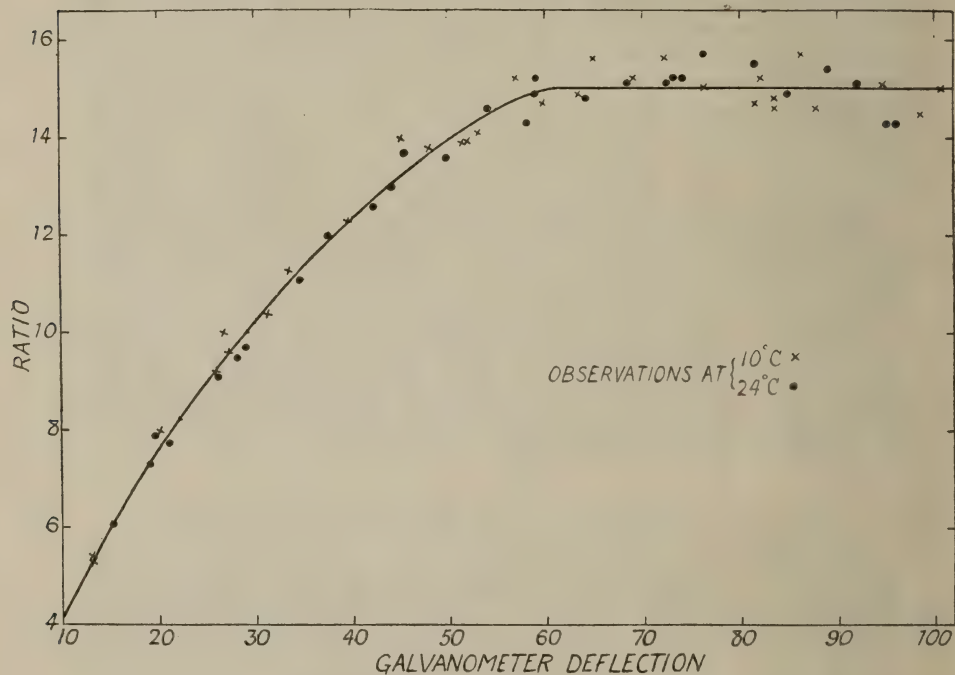


FIG. 3. Relationship of galvanometer deflexion to galv. deflex. $\div \sqrt[3]{\text{air vel.}}$

were placed 24 inches inside the mouth of the tunnel, so as to exclude the possible effects of air movements at the mouth.

The results of the observations are plotted in Fig. 3, abscissae indicating the galvanometer deflexion, and ordinates, the ratio of galvanometer deflexion to the cube root of the air velocity, as indicated by the kata. It will be seen that at a deflexion of 60 scale divisions and upwards the ratio was practically constant. It averaged 15.0, so the air velocity can be deduced from the galvanometer deflexion in accordance with the formula :

$$\text{Air velocity} = \left(\frac{\text{galv. deflex.}}{15.0} \right)^3$$

At lower deflexions the formula does not apply, and the factor with which to divide the observed deflexion has to be read off from the mean curve drawn in Fig. 3. It is probable that the cube root ratio would be found to hold nearly as well for the lower galvanometer

deflexions as for the higher ones if only we knew what is the true 'zero' deflexion. The zero taken was that shown by the galvanometer when the detector was screened from air currents, but under such conditions the hot wires were still losing a great deal of heat. Supposing we assume that this loss corresponded to a galvanometer deflexion of 50 scale divisions, and this amount be added to the observed readings, we get the following ratios :

Observed galv. deflex.	10	20	30	40	50	60	70	80	90	100
Observed deflex./ $\sqrt[3]{\text{vel.}}$	4.19	7.68	10.25	12.35	13.97	15.0	15.0	15.0	15.0	15.0
Corrected deflex./ $\sqrt[3]{\text{vel.}}$	25.1	26.9	27.3	27.8	27.9	27.5	25.7	24.4	23.3	22.5

It will be seen that the corrected ratio now varies in rough proportion to the cube root of the velocity throughout its range. It rises slightly and then falls off gradually, the reason being that there is not, and cannot be, any steady relationship between deflexion and air velocity over more than a limited range. At lower velocities, the deflexion varies approximately as the square root of the velocity ; at greater velocities, as the cube root, at greater ones still, as a higher root, till finally at very great velocities the deflexion is not further affected. The same variable relationships were observed in the cooling rates of the kata-thermometer. From the curves recorded by Hill, Vernon and Hargood-Ash (1922), it can be seen that at velocities above 12 metres per sec. the observations made with the dry kata-thermometer fall below the theoretical square root curve. The wet kata-thermometer, which owing to its wetted muslin glove cools about three times faster than the dry kata-thermometer, was found to cool at a rate varying approximately as the cube root of the velocity, but at high velocities it likewise showed a smaller response.

In order to determine the effect of temperature on the galvanometer deflexion, half of the observations were made approximately at 50° F. (10° C.), and the other half at 75° F. (24° C.). Considering only the observations made at a deflexion of 57 or more scale divisions, we found that, on an average :

16 observations at 50.6°	gave a ratio of 15.65			
15	„	75.2°	„	„ 14.40

This temperature effect corresponds to a difference of ± 0.05 in the ratio for each degree below or above the mean temperature of 63° F., and this correction has been applied to the data plotted in Fig. 3. It might be thought that at the lower galvanometer deflexions, when the ratios were considerably lower than 15.0, the temperature correction ought to be decreased proportionately, but it was found that the most consistent results were obtained by applying the full correction at all deflexions. Thus the data plotted in Fig. 3, which are corrected on this principle, are fairly evenly distributed about the mean curve.

4. THE MEASUREMENT OF TEMPERATURE VARIATIONS.

Air currents vary in temperature as well as in velocity, and it is possible that such variations may have some influence on the subjective sensations of air movement. In order to investigate their extent, we made a delicate thermopile of the form shown in Fig. 4. Thin wires of iron and nickel were soldered together (using resin as a flux), and the junctions were hammered out as thin as possible. Twenty of these junctions were fixed in a boxwood ring of 5.3 cm. internal diameter, and the lower ends were soldered together and connected up with three binding screws, whereby the whole series of couples could be connected with a galvanometer, or if desired, 13 or 7 of them. The ring with its thermo-couples could be pushed down so as to fit tightly in an annular trough, which prevented any access of air to the lower junctions. At first this trough was made of boxwood (as shown in Fig. 4), but for reasons given below we replaced it with a brass trough. The walls of this trough were 1.5 mm. thick, and were painted dead black.

The upper iron-nickel junctions were coated with lamp-black, and were bent inwards so as to catch currents of air passing vertically through the ring, as well as the horizontal currents. The galvanometer used was a unipivot dead-beat instrument, of the same type as that used with the hot-wire detector. Both thermopile and detector were fixed to the same stand, about 10 inches apart, and the galvanometers were read by two investigators synchronously with the beats of the metronome. We found that when this was set at $2\frac{1}{2}$ sec. intervals, there was sufficient time to read an instrument and record the reading in a note-book.

The thermopile was calibrated, after shutting the ring in the trough, by dipping the lamp-blackened junctions alternately in jars of water differing slightly in temperature. Six sets of six readings were taken at temperature differences of 1.6° to 3.6° F., and it was found that the resultant galvanometer deflexions amounted to 14.1, 13.0, 13.2, 14.0, 13.9, and 14.0, scale divisions per $^{\circ}$ F., or approximately to 14 divisions on an average.

The thermopile was subjected to a number of control observations of the following kind. The ring was first raised from the trough, and the instrument exposed to the air of the room till all parts were in temperature equilibrium. The ring was then shut down, and one investigator, holding the instrument at arm's length, walked backwards and forwards at the rate of about 1 ft. per sec. This was to imitate an average air velocity such as is often met with in factories. The other investigator read the galvanometer at 10 sec. intervals, and after a time the investigator carrying the thermopile went into an adjoining room, the temperature of which was 2° to 4° F. higher than that in the first room. As can be seen from the sample record shown in the lower half of Fig. 5, the galvanometer deflexion reached its maximum change in about 20 secs., and then slowly moved towards equilibrium. This was due to the heat from the room gradually penetrating the brass walls of the trough, and warming the lower junctions. After six minutes the ring was raised so as to expose the junctions, and it will be seen that the galvanometer deflexion

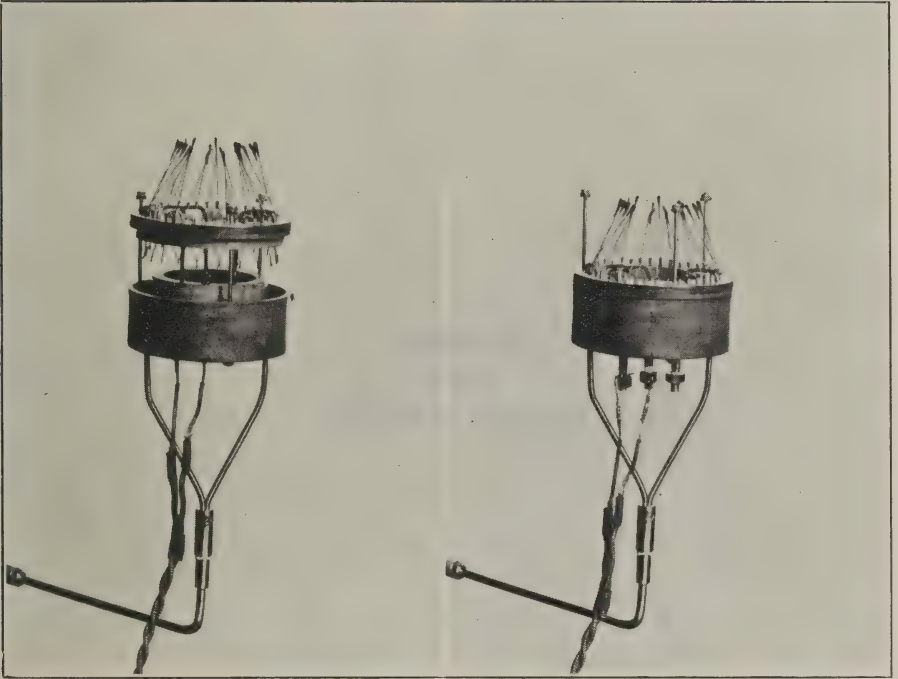


FIG. 4. The thermopile, open, and closed.

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speedily rose almost to zero, indicating temperature equilibrium. As would be expected, a subsequent shutting down of the ring caused but little galvanometric change. The investigator then carried the instrument back into the other room, and the galvanometer showed the reverse changes. The maximum change of deflexion was 43 scale divisions on passing from the cool to the warm room, and 41 divisions on passing back again. As the rooms differed in temperature by 3.0°F. , it follows that the mean fluctuation corresponded to 14 divisions per $^{\circ}\text{F.}$, or the same as in the afore-mentioned calibrations.

In the upper part of Fig. 5 is shown a corresponding experiment in which the boxwood trough was used instead of the brass one. It will be seen that, on passing from the cool to the warm room, the deflexion moved towards equilibrium much less rapidly than

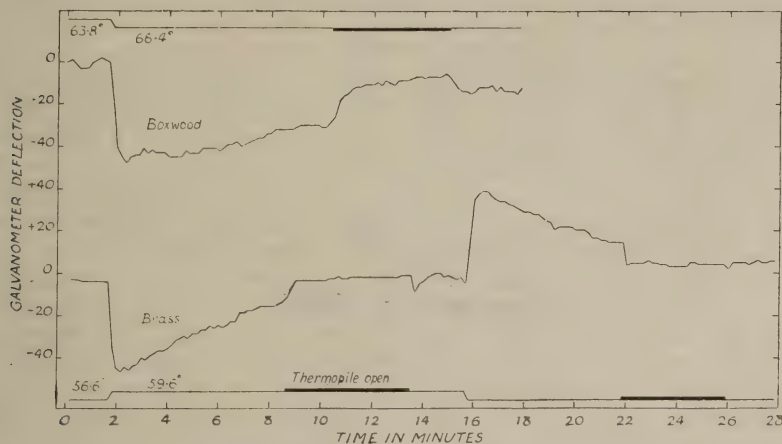


FIG. 5. The response of the thermopile to temperature changes.

before, owing to the poorer conduction of heat by the wood. When the ring was raised the deflexion did not rise to zero, probably because the wood was still giving some heat to the lower junctions. Undoubtedly it had not taken up the air temperature completely, for on shutting down the ring again it will be seen that the galvanometer speedily showed a fall of about 10 scale divisions. It was because of the slowness of the boxwood trough to take up the air temperature that it was discarded. If, previous to use, the apparatus had been left for some time in a place considerably warmer or cooler than that under investigation, it had to be left exposed for over half an hour before it got thoroughly into temperature equilibrium, whilst the brass trough needed only about ten minutes.

5. A COMPARISON OF THE HOT-WIRE ANEMOMETER AND THE THERMOPILE.

A further series of experiments was made in order to prove that whilst the hot-wire anemometer was almost exclusively affected by changes of air velocity, the thermopile was only affected by changes of temperature. The thermopile and detector were placed at the

mouth of the tunnel previously mentioned, but the air current was cut off from them by interposing a wooden board. The galvanometers were read at $2\frac{1}{2}$ sec. intervals, and after a time the board was suddenly withdrawn. It will be seen in Fig. 6 that the galvanometer connected with the detector showed a maximum deflexion in less than 10 secs., whilst that connected with the thermopile showed practically no change. On interposing the board again the galvanometer attached to the detector showed a quick fall to an air velocity of about 40 ft. per min., and then a very gradual subsidence, so that the original low velocity was not reached for $1\frac{1}{4}$ mins. This was due to the air current from the tunnel bounding and rebounding from the walls and other objects in the room (cf. Part III of this Report).

Converse series of experiments were made by placing the detector and thermopile in one half of a large copper chamber, separated from the other half by a sheet of asbestos. In this second half a slightly warmed slab of iron, weighing 10 lb., was placed on a paper pad, so as to prevent heat conduction. Both halves of the chamber were covered up with asbestos sheets, and galvanometer readings were taken at $2\frac{1}{2}$ sec. intervals. When the intervening sheet of asbestos was removed, the thermopile soon indicated a temperature rise of about 2° F. (see Fig. 7), whilst the anemometer showed that there was practically no change of air velocity except for the small initial one due to moving the asbestos sheet. It may be remarked that the thermopile was rather slow in responding to the temperature change, but it must be remembered that it would take some time for the iron slab to warm the whole of the air in the chamber evenly. On reinserting the asbestos sheet the thermopile showed only a gradual fall of temperature, for naturally the air took some time to cool.

The fact that the thermopile does respond very quickly when placed in a rapid current of air of a different temperature is indicated by the curve in Fig. 8. This was obtained by placing the thermopile alternately on a bench where the air velocity was 26 ft. per min., or close to a plenum inlet where its velocity was 148 ft., and its temperature 4° cooler. It will be seen that on transferring the thermopile from the rapid current to the slow one, the galvanometer deflexion was a good deal slower in approaching equilibrium.

Synchronous records of the variations in air velocity and temperature experienced at several factories are reproduced in Part III of this Report.

6. SUMMARY.

In order to measure the rapid oscillations of air velocity which are always present in factories and other rooms, a 'hot-wire' anemometer was designed consisting of three platinum wires in three planes at right angles. The wires formed part of a Wheatstone bridge, and a 0.5 amp. current heated them to about 130° C. The changes of resistance produced by variations in the velocity of the air currents were indicated by a galvanometer, which was read at $2\frac{1}{2}$ sec. intervals. The apparatus was calibrated by comparing it against a kata-thermometer in a small wind tunnel.

In order to measure rapid oscillations of air temperature, a thermopile consisting of 20 iron-nickel junctions was designed.

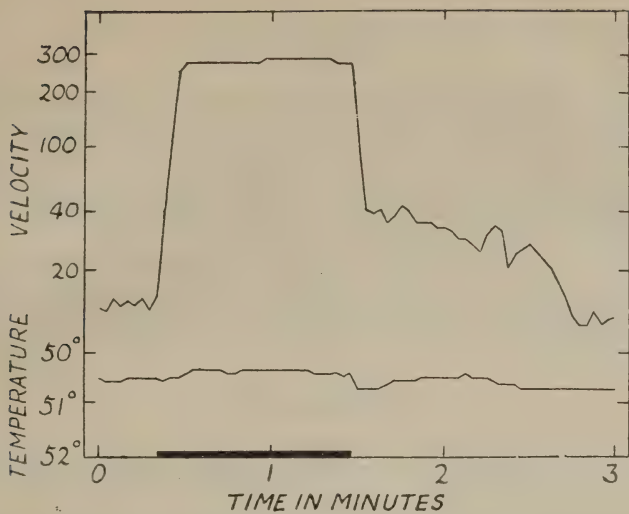


FIG. 6. Exposure of hot-wire detector and thermopile to rapid air current.

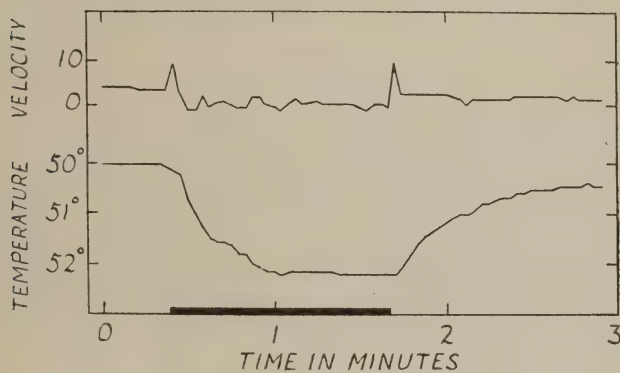


FIG. 7. Exposure of hot-wire detector and thermopile to warm air.

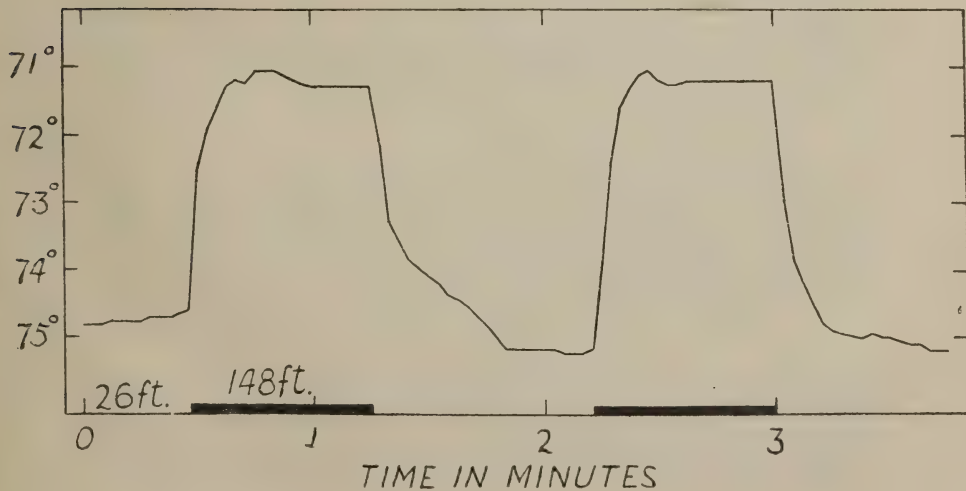


FIG. 8. Exposure of thermopile to current of cool air.

The wires were fixed to a wooden ring, and the upper junctions were hammered very thin, whilst the lower ones were protected by an annular trough of brass (or wood). The thermopile was connected to a dead-beat galvanometer. It was calibrated by dipping it into water at different temperatures, and by taking it from one room to another of a different temperature.

Control observations showed that the thermopile was unaffected by changes of air velocity, though rapidly responsive to changes of air temperature, whilst the hot-wire anemometer showed the reverse response.

REFERENCES.

- HILL, L., VERNON, H. M., and HARGOOD-ASH, D. (1922): *Proc. Roy. Soc., B.*, **93**, 198; also HARGOOD-ASH, D., and HILL, L. (1923): *Medical Research Council, Special Report*, No. **73**, 14.
KENNELLY (1909): *Tr. Am. Inst. Electr. Eng.*, **28**, 363.
KING, L. V. (1914): *Phil. Tr. Roy. Soc., A.*, **214**, 373.
MACGREGOR-MORRIS, J. T. (1912): *The Electrician*, **69**, 1056.
SER (1888): *Traité de Physique industrielle*, **1**, 142.

PART II. THE CALIBRATION OF THE KATA-THERMOMETER

BY

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1. INTRODUCTION.

THE relationship between air velocity and the rate of cooling of the kata-thermometer was investigated by Hill, Vernon and Hargood-Ash (1922) at room temperature, and no attempt was made to determine if the formulae arrived at held equally well through a range of temperature. It was found that the results obtained at velocities of less than one metre per second did not follow the same formula as those obtained at higher velocities, presumably owing to the disturbing effects of the convection currents of hot air which rise from the bulb of the kata. The low velocity observations were made by the 'whirling arm' method, at an average temperature of 57° F., whilst those at velocities over a metre per second were made, chiefly in wind tunnels, at an average temperature of 67°. I obtained indirect evidence that the kata formulae do not hold equally well through the range of temperature commonly met with in factories, so I thought it desirable to make fresh series of observations at various well-defined temperatures. The results obtained indicate a considerable temperature effect.

2. THE FACTOR OF THE KATA-THERMOMETER.

The temperature effect is due chiefly to variations in the 'factor' of the kata-thermometer, though it is theoretically a constant, as it represents the number of millicalories given out by the kata in cooling from 100° to 95° F., divided by the surface area of the bulb in square centimetres. It is calculated from the formula :

$$K = 0.27 (36.5 - t) \phi,$$

where ϕ is the time, in seconds, required by the kata to cool from 100° to 95° F. in a still air chamber at a temperature t . Hill, Griffith and Flack (1916) found that the factor is practically constant over a considerable range of temperature, but Angus (1924) found that whilst an

ordinary kata had a constant factor at temperatures of 10° to 20° C., it showed a rather rapid rise at higher temperatures. An electric kata showed a gradual rise in its factor at all temperatures. Angus rightly attributed the variability of the factor to the convection currents of hot air which are set up in the still air chamber, for these currents tend to get less and less rapid the higher the temperature. For this reason one would expect the factor to show a gradual increase with rise of temperature, and not a steady level below 20° C., followed by a rise.

The accurate determination of the factor is not easy, as it is much influenced by very small variations in the temperature of the surrounding air, and this temperature is to some extent affected by the heat derived from the cooling kata. I made most of my observations in a large copper water-jacketed chamber, the internal measurement of which was 25×17 inches, by 12 inches deep. The bulbs of the kata and of the thermometer were kept 15 inches from the floor of the chamber, and 9 inches apart. The chamber contained 70 litres of water, and its temperature remained very steady. Observations were made with three katas, four determinations of cooling time (or three, at the high temperatures) being made at each temperature, and a mean taken. The mean temperature at which the observations were made with two of the katas was the same, viz. 20.2° C., whilst the observations on the third kata were at 19.4° , and in order to make the results comparable, a hypothetical value is included, and recorded in the Table in brackets. This brings the mean temperature to the same level, whilst the factor corresponding to the hypothetical value was deduced from the other values. All the factors of each kata were converted into percentages on the respective means, and they are recorded in this form in Fig. 1 (except the hypothetical value).

Kata A.			Kata B.			Kata C.		
Temper- ature.	Factor.	Factor as per cent.	Temper- ature.	Factor.	Factor as per cent.	Temper- ature.	Factor.	Factor as per cent.
$^{\circ}$ C.			$^{\circ}$ C.			$^{\circ}$ C.		
9.33	456.2	95.2	9.85	472.2	95.0	9.93	456.8	94.9
13.71	461.9	96.3	13.80	475.4	95.7	13.71	460.0	95.7
14.04	464.2	96.8	14.14	473.2	95.3	14.10	459.7	95.6
15.58	460.5	96.0	15.78	482.7	97.2	15.86	470.8	97.9
19.77	476.6	99.4	19.80	495.6	99.8	19.90	479.8	99.8
21.74	483.4	100.8	22.12	499.5	100.5	—	—	—
22.04	481.4	100.4	—	—	—	—	—	—
24.50	486.6	101.5	24.36	505.1	101.7	24.53	498.9	103.7
24.86	491.1	102.4	24.82	496.1	99.9	(27.09)	(500.7)	(104.1)
27.04	505.9	105.5	27.42	519.7	104.6	27.53	504.6	104.9
29.80	507.2	105.8	30.00	548.3	110.4	29.45	496.7	103.3
20.26	479.5	100.0	20.21	496.8	100.0	20.23	480.9	100.0

It will be seen that there is approximately a linear relationship between the factor and the temperature of the chamber. The observations with different katas are indicated by different signs, and those surrounded by circles were made in a smaller air chamber. The large chamber had a thick plate-glass panel inserted in the door, through which the instruments were read, but as the room temperature was different from that of the chamber, it was thought that a

small degree of air movement might be induced thereby. Hence a further series of observations was made with a copper water bath, 15 inches square, which was fitted with a metal lid. It had a plain glass front, but in order to exclude any possibility of induced air currents, the room in which the observations were made was kept at a steady temperature of 10° , 14° or 24° , and the cooling time determined after the temperature of the bath had got into equilibrium with it. These observations are in moderately good agreement with the others, and the line drawn through them all indicates that the factor has a variation of 0.59 per cent. for each $^{\circ}$ C. above or below 20.2° , or one of 0.33 per cent. for each $^{\circ}$ F. As already stated, the kata formula for low velocities was determined at 57° F., and with this temperature as a mean the factor works out at 0.34 per cent. for each $^{\circ}$ F.

The factor marked on the stem of kata-thermometers by the maker

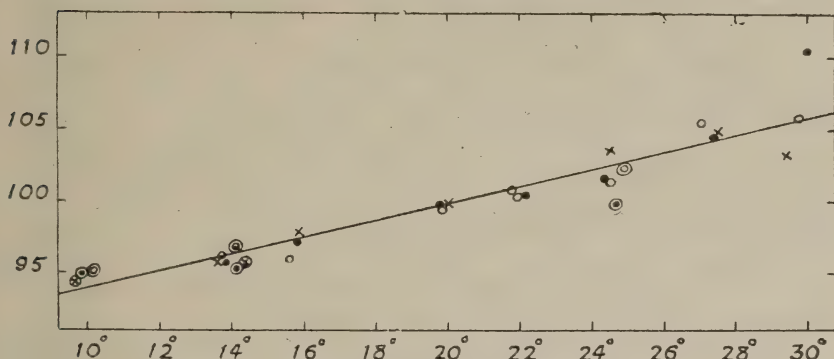


FIG. 1. Influence of temperature on the factor.

has hitherto been determined at an unspecified room temperature. It is suggested that in future, whatever the temperature at which it is actually determined, it be corrected to some standard temperature, e. g. 60° F.

3. THE EFFECT OF TEMPERATURE ON THE AIR VELOCITY RELATIONSHIP.

The effect of temperature on the relationship between air velocity and H/θ was investigated by the whirling arm method. The apparatus consisted of a wooden strip, six feet in length, fixed to a central pillar screwed to a pulley wheel which ran on ball bearings. This was connected with a set of reducing pulleys and an electric motor, the speed of which was varied by changing the resistance. The kata was clamped to one arm at a distance of 92, 46 or 17 cm. from the centre, and at first a corresponding weight was fixed to the other arm, but later on this was replaced by the recording thermometer. The observations were made in a room 16×12 ft. in size, and in order to reduce draughts all but one of the windows, and that a double glass one, were covered up, whilst an artificial roof of brown paper, supported on strings, was made above the revolving arm, and a similar floor below it. Thereby the kata was made to revolve in the middle of a horizontal space $2\frac{1}{2}$ ft. deep. The room was heated with hot-water pipes, but these were insufficient to get the temperature to the

chosen level (75° F.), so gas burners, heating sheets of asbestos, were placed at each corner of the room, 3 ft. from the revolving arm. Once the temperature was attained, they were turned low. The cool air observations were made at 50° F., the natural temperature of the unheated room.

At first the temperature of the air was taken with a thermometer fixed a foot from the revolving arm. When subsequently a thermometer was clamped to the moving arm, it was found that its temperature agreed with that of the stationary thermometer to within 0.1° C. The thermometers used, which could be read to 0.01° C., were calibrated against a set of standard thermometers (Kew verified).

The true velocity of the moving kata, relative to the air, is less than the actual velocity, because the air is to some extent carried round by the moving arm. The correction needed for this 'swirl' was determined by a method similar to that described by King (1914). In our previous observations the revolving arm apparatus used by me consisted of a one-armed metal rod, and this was found to cause a swirl corresponding to a correction of 6 to 7 per cent. in the velocity, whilst Hill and Hargood-Ash used a double arm, and this caused a swirl corresponding to a 9 per cent. correction. In the present observations I likewise found a swirl corresponding to 9 per cent., and this correction was applied to all the results described. In making the observations the rate of cooling was determined four times at each velocity, and a mean taken. As the motor was not very steady, the rate of revolution of the arm was determined immediately before and immediately after each cooling time determination.

The results are plotted in Fig. 2, and it will be seen that, for a given air velocity, considerably lower H/θ values were observed at 75° F. (24° C.) than at 50° F. (10° C.). The continuous line drawn through the lower set of results corresponds to the formula :

$$H/\theta = 0.20 + 0.40 \sqrt{v}.$$

It will be seen that the effect of temperature got less and less as the velocity increased, and it is believed that this was due chiefly to the diminution of the convection current influence. At low air velocities the fairly rapid convection currents rising vertically from the hot kata bulb are swept aside only to a moderate extent by the horizontal air currents, but as the air velocity gets greater and greater they are displaced more and more, till at a velocity of 1 metre per second it appears—if our formula is correct—that their influence is reduced to zero. I have assumed, therefore, that at an H/θ of 0.27 the convection current effect is the same as that influencing the factor (viz. 0.34 per cent. for each ° F.), and that it falls steadily to zero as the H/θ increases to 0.60 (the value corresponding to an air velocity of 1 metre per sec.).

In addition to the convection current influence there is another independent one, which is also observed at velocities greater than 1 metre per sec. This is indicated by the data plotted in the upper part of Fig. 2. It will be seen that the observations made at 10° C. show, on an average, a distinctly higher H/θ value than those made at 24° C. The continuous line drawn through them corresponds to our formula :

$$H/\theta = 0.13 + 0.47 \sqrt{v}.$$

The cold air observations were made at a mean temperature of 10.12°C ., and the hot air ones at one of 24.02°C . The corresponding mean H/θ values observed were (after introducing a small correction to bring the data to the same mean air velocity) 0.7422 and 0.7244 respectively. This difference corresponds to a correction of 0.10 per cent. for each degree *Fahrenheit* above or below 67°F . (the mean temperature at which the above formula was ascertained). The dotted lines drawn on either side of the continuous line are in

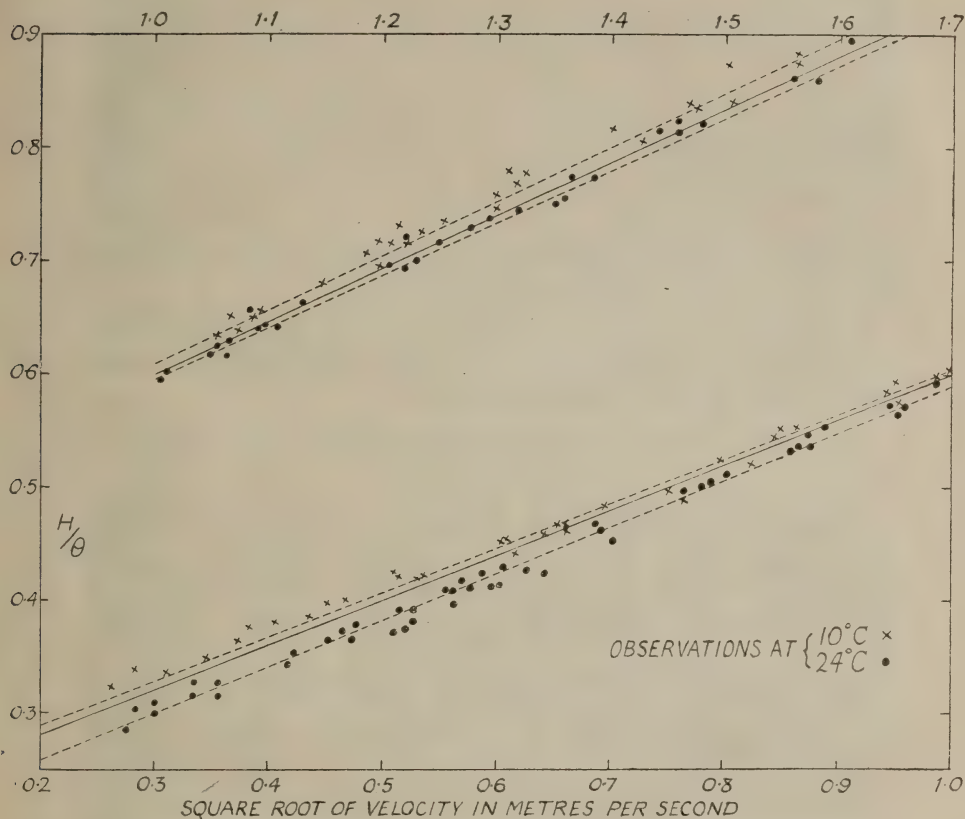


FIG. 2. Relationship between H/θ and air velocity at various temperatures.

accordance with the temperature correction calculated from this mean. The observed values do not agree very closely with them, but this is largely because of the errors inherent in the revolving arm method, which is not so accurate at velocities above 1 metre per sec. as at lower velocities. Still, it is the only method available, as wind tunnel observations cannot be made at velocities of less than about 3 metres per sec. In any case, the calculated correction is a small one, which only slightly affects the accuracy of the results. For instance, an H/θ of 0.70, if determined at temperatures of 57° and 77° instead of at 67° , would be raised or lowered only to 0.707 and 0.693 respectively. Equally great variations would be caused by errors of 0.4° and 0.2°F . in measuring the air temperature.

The cause of this small temperature effect is uncertain, but it may

be due to differences in the humidity and density of the air. Petavel (1898) found that the rate of cooling of a platinum wire heated to 74° – 171° C. was about 10 per cent. less in air of ordinary humidity than in air saturated with moisture, whilst I found (1923) that in air moving with a velocity of 40 ft. per min. the kata cooled about 7 per cent. more rapidly in saturated air than in ordinary air. On the other hand, Angus (1924) found that humidity did not affect the cooling rate of a kata kept in a still air chamber. In the present observations, the humidity of the air in the calibrations made at 75° corresponded to a saturation of 65 per cent., and of those made at 50° , to one of 80 per cent. Possibly, therefore, the whole of the observed temperature effect at the greater air velocities was due to differences of humidity; but even if this were so, it does not detract from its practical significance, for humidity observations made in factories show somewhat similar differences of humidity at 50° and 75° F. Unpublished observations recently made by T. Bedford, C. G. Warner and myself in various factories, chiefly those concerned in boot and shoe production, showed that in the 76 observations made at 47.5° – 52.4° F. (mean 49.6°) the average saturation was 73 per cent., whilst in the 308 observations made at 72.5° – 77.4° (mean, 74.8°) it was 49 per cent.

In addition to the effect of reduced humidity, it is probable that moving air at 75° , being 5 per cent. less dense than air at 50° , carries away slightly less heat from the cooling kata.

4. THE CALCULATION OF THE AIR VELOCITY AT VARIOUS TEMPERATURES.

If the correction of the H/θ values, due to convection currents, be assumed to vary from 0.34 per cent. per $^{\circ}$ F. at a value of 0.27 down to zero at one of 0.60, whilst the correction due to other causes be taken as 0.10 per cent., whatever the H/θ value, it follows that the total correction ranges from 0.44 per cent. down to 0.10 per cent. The dotted lines plotted in the lower record of Fig. 2 are drawn in accordance with this calculation, and it will be seen that the observed values agree moderately well with them. Both at 10° C. and at 24° C. they are somewhat too high at low velocities and somewhat too low at medium velocities, but just the same lack of correspondence was observed by us in our previous observations. Probably it would be impossible to fit the experimental values accurately by any formula because of the gradually diminishing effect of the convection currents, but in any case the deviations are not considerable.

It may be contended that the explanations I have adduced to account for the observed temperature effect are of doubtful validity, but even if they are incorrect the dotted lines drawn on the assumption of their correctness agree fairly well with the experimental values. If it be thought more satisfactory, they could be replaced by curves drawn empirically through the observed values. On the assumption that the theoretical curves are approximately correct I have calculated the subjoined Table of equivalents between H/θ (i. e. the actually observed values) and air velocity at various temperatures. The velocity is given in feet per second and the temperature in degrees Fahrenheit, as these measures are more convenient for industrial purposes. It is to be remembered that for H/θ values of less than 0.60 the standard temperature (to which our formula applies

without correction) is 57° F., whilst for those of 0.61 or more the standard temperature, to which the other formula applies without correction, is 67° F. It is of interest to note that, according to the Table, an observed H/θ of 0.27, which on the old formula did not correspond to any measurable air velocity, is now shown to correspond to one of 12 ft. per min. at 80° . May Smith (1922), in her observations in laundries, where the air temperature was often 80° – 90° , sometimes observed an H/θ value of 0.27 or less. The reason of this is now made clear.

It should be stated that in calculating the equivalents in the Table the corrections were applied by working backwards. For instance, it was calculated that at a temperature of 80° an H/θ of 0.331 (equivalent to a velocity of 21 ft. per min.) would, with due correction, be reduced to an H/θ of 0.30. Supposing, however, the correction had been added on to the observed H/θ value of 0.30, it would have raised it only to 0.328 (equivalent to a velocity of 20 ft. per min.).

TABLE I. *Relationship between Air Velocity and H/θ at various Temperatures.*

Observed H/θ .	Percentage correction which has been applied for each $^{\circ}$ F.	Velocity in feet per minute at						
		50° .	55° .	60° .	65° .	70° .	75° .	80° .
0.27	0.44	—	—	—	8	9	10	12
0.28	0.43	—	—	9	10	11	13	15
0.29	0.42	8	10	11	12	14	16	18
0.30	0.41	10	12	13	15	17	19	21
0.31	0.40	12	14	16	18	20	22	24
0.32	0.39	15	17	19	21	23	26	28
0.33	0.38	18	20	22	24	26	29	32
0.34	0.37	21	23	26	28	30	33	36
0.35	0.36	25	27	29	31	34	37	41
0.36	0.35	28	30	33	36	39	42	45
0.37	0.34	32	34	37	40	43	46	49
0.38	0.33	36	39	42	44	47	51	54
0.39	0.32	41	44	46	49	52	56	60
0.40	0.31	45	48	51	54	58	62	66
0.41	0.30	50	53	56	60	63	67	71
0.42	0.29	55	58	62	65	69	73	77
0.43	0.28	61	64	68	71	75	79	83
0.44	0.26	67	70	73	77	80	84	88
0.45	0.25	72	76	79	82	86	91	95
0.46	0.24	78	82	85	89	93	97	101
0.47	0.23	84	88	92	96	100	104	108
0.48	0.22	92	95	99	102	106	111	115
0.49	0.21	99	102	106	110	114	118	122
0.50	0.20	106	110	113	117	120	125	129
0.51	0.19	113	117	120	125	129	133	137
0.52	0.18	121	125	128	132	136	140	144
0.53	0.17	129	133	136	140	144	148	152
0.54	0.16	137	141	144	148	152	156	160
0.55	0.15	145	149	152	157	160	164	169
0.56	0.14	155	158	161	165	169	172	177
0.57	0.13	164	168	170	174	178	182	186
0.58	0.12	173	177	180	184	186	190	193
0.59	0.11	183	186	189	192	195	199	202
0.60	0.10	193	196	199	202	204	207	209

At all higher H/θ values the correction is ± 0.10 per cent. for each degree above or below 67° F. (but in above data the standard temperature was 57° F.).

5. THE RESPONSE OF THE KATA-THERMOMETER AND THE HOT-WIRE ANEMOMETER TO VERTICAL AIR CURRENTS.

As has been mentioned in Part I of this Report, the hot-wire anemometer was calibrated against the kata-thermometer in a small wind tunnel, which was placed horizontally. The tunnel and the electric fan were screwed to a board, which could be fixed in a vertical position so as to yield either descending or ascending currents. Series of observations were made with the two instruments, and in order to control the results, a vane anemometer was tested as well. This latter instrument is four inches in diameter, and its actual readings needed considerable corrections to give the true velocity. It was not calibrated by the makers (Negretti and Zambra) below the velocity of 300 ft. per min., but I was able to calculate calibrations by extrapolation which gave results in fair agreement with velocities of 100 ft. and upwards as ascertained by the kata. In a number of the (horizontal) wind tunnel observations previously described the vane anemometer was tested over $1\frac{1}{2}$ to 2 min. periods, in the same two positions as the kata and the hot-wire anemometer, and the data adduced in Table II show a fair correspondence, though the reason of the higher ratio observed at 50° than at 75° is unknown. It must be remembered that the two instruments were not compared at exactly the same time, but consecutively. If they had been, the correspondence might have been a little closer.

TABLE II. *Comparison of Velocities indicated by Kata-Thermometer and Vane Anemometer.*

Kata. ft.	At 50° F. Anemometer.	Ratio.	Kata. ft.	At 75° F. Anemometer.	Ratio.
	ft.			ft.	
112	122	1.09	126	140	1.11
147	145	0.98	129	137	1.06
136	157	1.15	164	163	0.99
169	193	1.14	209	189	0.90
195	206	1.06	218	220	1.01
213	251	1.18	258	255	0.99
277	315	1.14	332	335	1.01
280	320	1.14	346	329	0.95
Mean		1.11			1.00

When investigating the effects of descending air currents, the kata was clamped so that its bulb was 11 inches from the mouth of the tunnel, and the customary 4 inches from the sides. It was illuminated by a small electric lamp placed three feet above it in the tunnel, and was read through two small peep-holes made in the walls of the tunnel. The hot-wire detector was placed opposite to it in a corresponding position, and the instruments were subsequently changed round, as in the horizontal tunnel observations. The results obtained are recorded in Table III, and it will be seen that they differ remarkably from the horizontal tunnel observations. Assuming that the vane anemometer results are approximately correct, we see that at a velocity of about 300 ft. per min. the kata indicated a velocity only a third as great, whilst at a velocity of about 100 ft. per min. it indicated one which was only a fourth to

a sixth as great. The hot-wire anemometer, on the other hand, showed 70 per cent. the theoretical velocity in air at 75°, and 60 per cent. the theoretical in air at 48°. The reason why the kata gives so extraordinarily inaccurate a measure of these somewhat considerable air velocities must be due chiefly to its cylindrical shape. The area of the bulb impinged on by the descending currents is so much smaller than that affected by horizontal currents that it gives up its heat much more slowly. In addition, it must be remembered that under ordinary circumstances convection currents of warm air

TABLE III. *Descending Air Current*

Air at 48°.						Air at 75°.					
Velocity in ft. per min. shown by :			(a) as per cent. on (b).	(a) as per cent. on (c).	(b) as per cent. on (c).	Velocity in ft. per min. shown by :			(a) as per cent. on (b).	(a) as per cent. on (c).	(b) as per cent. on (c).
(a) kata.	(b) hot-wire.	(c) vane anemom.				(a) kata.	(b) hot-wire.	(c) vane anemom.			
(0-269)	5	—	Fan stopped			(0-271)	7	—	Fan stopped		
(0-251)	9	—	Fan very slow			(0-237)	(-4)	—	Fan very slow		
(0-253)	15	—	Fan very slow			(0-241)	15	—	Fan very slow		
(0-272)	29	—	—	—	—	8	30	—	27	—	—
10	39	—	26	—	—	14	41	—	34	—	—
16	58	103	28	16	56	23	70	98	33	23	71
46	112	178	41	26	63	48	125	176	38	27	71
98	186	302	53	33	62	96	198	290	48	33	68

are rising with a fair speed from the warm bulb, and the descending current has to counteract and reverse these currents before it effectively cools the bulb. This fact is well brought out by the data obtained at velocities below 100 ft. per min. We see that, as compared with the velocity indicated by the hot-wire detector (for the vane anemometer was no longer available), the velocity indicated by the kata is still lower than at velocities above 100 ft., and at the lowest velocities the kata gave H/θ values of less than 0.27. When the fan was stopped altogether, the H/θ observed approximated to 0.27, in accordance with expectation, but with a very slow fan it sank as low as 0.237. This was because the ascending convection currents of warm air were met by descending currents of similar velocity, whereby the air surrounding the bulb was rendered much more stagnant than if there had been no descending current at all.

The hot-wire detector suffers from the defects shown by the kata in much smaller degree, as the convection currents rising from its hot wires are so much weaker because of the very small mass of the wires. Yet in one instance I was able to hit on approximately the right descending air current to neutralize them, and the galvanometer showed a negative reading of 4 scale divisions. In all the other instances the hot-wire detector indicated a small positive velocity, and as already mentioned, at high velocities it showed 60 to 70 per cent. the velocity indicated by the vane anemometer. The fact that it did not give a result approximating more closely to the theoretical is due partly to the fact that the ascending

convection currents had to be counteracted and reversed, and partly to the resistance to vertical air currents offered by the connecting wires and supporting framework of the detector.

A series of observations made with *ascending* air currents is recorded in Table IV. It was not feasible to fix the kata with its

TABLE IV. *Ascending Air Current at 53°.*

Velocity in ft. per min. shown by :			(a) as	(a) as	(b) as
(a)	(b)	(c) vane	per cent.	per cent.	per cent.
kata.	hot-wire.	anemom.	on (b).	on (c).	on (c).
(0.277)	5	—		Fan stopped	
14	15	—	93	—	—
17	19	—	90	—	—
24	26	—	92	—	—
28	35	—	80	—	—
35	51	—	69	—	—
55	90	109	61	50	83
93	148	212	56	39	70
128	223	321	57	40	69

bulb more than six inches beneath the mouth of the tunnel, and the detector was placed at a corresponding level. As the air current was now moving in the same direction as the convection currents, it might be thought that the kata would indicate a greater air velocity than the theoretical, but this was not so, for the reason already given, viz. the small area of bulb exposed to the ascending current. Still, the kata responded much better than it did to descending currents, and the slower the ascending current the better its response, whilst we saw that with descending currents the reverse relationship held. The hot-wire detector likewise responded better than with descending currents, and it likewise responded best of all with slow ascending currents, but it never indicated the theoretical velocity, presumably because of the obstructions it offered to vertical currents. At low velocities the kata indicated nearly as high values as the hot-wire detector, and presumably, therefore, it gave a result not very different from the true velocity.

The observations recorded were made at 53°, and a further series was attempted at 75°, but it was found to be impossible to get the air temperature of the room sufficiently uniform. The fan was sucking relatively cool air from the neighbourhood of the floor of the room, and discharging it near the ceiling, where relatively hot air had collected. Hence the air outside the tunnel was warmer than that inside, and the results obtained, though they supported those recorded in Table IV, were rather erratic.

For practical purposes we may conclude that the kata indicates somewhat lower air velocities than the theoretical when subjected to ascending air currents, and entirely unreliable air velocities when subjected to descending currents. In factories descending currents are often observed from skylights and windows, though they are seldom if ever purely descending. What fraction of the average air current is descending and what fraction horizontal or ascending it is impossible to say, but it will be seen from Part III of this Report that the hot-wire anemometer usually indicated greater velocities than the kata. The summer observations showed the hot-wire velocity to be about 20 per cent. greater than that indicated by

the kata, whilst the winter observations showed it to be about 10 per cent. greater. This smaller difference may have been due to the skylights and windows being closed, and thereby reducing the down draughts.

It is to be noted that the above data indicate an error of the kata only so far as it is used for the measurement of the actual air velocity. They do not prove that the kata is incorrect as an instrument for measuring cooling power. The human body, just like the kata, is surrounded by strata of warm ascending convection currents, and presumably they are affected by descending air currents in a similar fashion to those of the kata. Whether they affect subjective sensations of air movement in the same way that they affect the cooling power of the kata is unknown.

The question arises as to whether the cylindrical form of the

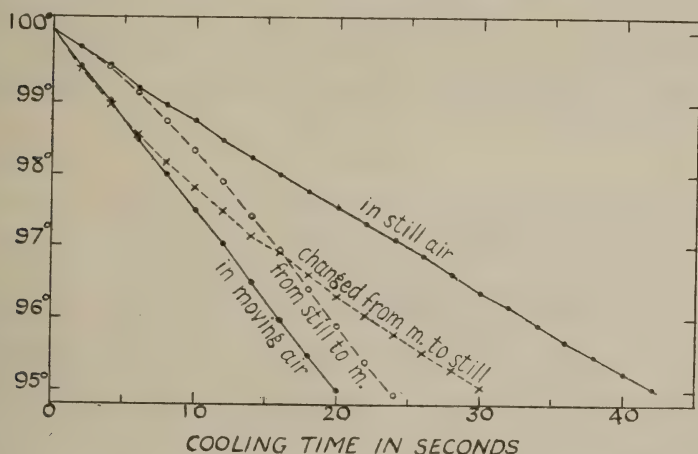


FIG. 3. The effect of moving air on the rate of cooling.

kata bulb is the most suitable shape. A spherical bulb would react more equably to vertical and horizontal air currents, but if this form were substituted, all the constants of the instrument would have to be re-determined. The cylindrical bulb corresponds better with the shape of the human body than a spherical one, but it would correspond better still if it were made longer and narrower than at present. Perhaps the shape of bulb now adopted is a good compromise between these two extremes.

6. THE INERTIA OF THE KATA-THERMOMETER.

The slowness in the response of the cooling kata to changes in air velocity is greater than might be supposed. Information on the point was obtained by reading the cooling kata at two second intervals synchronous with the ticks of a metronome. The kata was allowed to cool (a) when protected from the air current of an electric fan by means of a tin ($5 \times 3\frac{1}{4}$ inches in size); (b) when exposed to this air current; (c) when protected from the current by the tin only until the moment it had cooled to the 100° mark; and (d) when exposed to the current only until it had cooled to the

100° mark. Six sets of readings were taken under each of these four conditions, and the mean cooling rates are plotted in Fig. 3.

The observations were made at a mean temperature of 49.3°, and it will be seen that in still air the kata took 42.5 secs. to cool to 95°, whilst in moving air it took 20.0 secs. (indicating an air velocity of 510 ft. per min.). When the kata was exposed to the moving air only from the moment it had cooled to the 100° mark, it took 23.8 secs. to cool instead of 20.0 secs., and it will be seen from the curve that for the first 4 secs. of exposure it cooled no quicker than the protected kata, though it attained its full cooling rate after 12 secs. When, on the other hand, the kata was protected from the air current only from the moment of its cooling to the 100° mark, it took 30.4 secs. to cool instead of 42.5 secs., and the curve indicates that 22 secs. or more elapsed before the cooling rate became steady. That is to say, when the kata is transferred from a rapid air current to a slow one, it is much longer in getting into equilibrium than when it is transferred from a slow current to a rapid one. Hence it follows that in a variable air current the kata tends to over-estimate the mean velocity.

7. SUMMARY.

The 'factor' of the kata-thermometer is not constant. Observations made on three katas in two forms of chamber showed that it varied by ± 0.34 per cent. for each degree above or below 57° F.

Owing to the variability of the factor and to a less extent to other reasons, the relationship between the H/θ values and air velocity is considerably affected by temperature. The temperature correction which has to be applied to the ascertained H/θ is smaller and smaller the greater its magnitude, for it ranges from 0.44 per cent. per ° F. with an H/θ of 0.27 to one of 0.10 per cent. with an H/θ of 0.60 and upwards. A table of equivalents between H/θ and air velocity at various temperatures has been constructed.

By means of a small wind tunnel, which could be fixed vertically as well as horizontally, the response of the kata and the hot-wire anemometer to vertical air currents was tested. The kata is quite unreliable for measuring descending currents, for with an air velocity of 300 ft. per min. it indicates only a third the theoretical, and at lower velocities it gets more and more inaccurate, till at very low velocities it gave an H/θ of 0.24. The hot-wire anemometer indicates about two-thirds the theoretical velocity (as measured by vane anemometer).

With slow ascending air currents the kata is moderately accurate, but at high velocities it indicates considerably lower values than the theoretical.

REFERENCES.

- ANGUS, T. C. (1924): *J. Indust. Hyg.*, **6**, 21.
 HILL, L., GRIFFITH, O. W., and FLACK, M. (1916): *Phil. Tr. Roy. Soc., B.*, **207**, 183.
 HILL, L., VERNON, H. M., and HARGOOD-ASH, D. (1922): *Proc. Roy. Soc., B.*, **93**, 198; also *Medical Research Council, Special Report*, No. 73, 140.
 KING, L. V. (1914): *Phil. Tr. Roy. Soc., A.*, **214**, 373.
 PETAVEL, J. E. (1898): *Phil. Tr. Roy. Soc., A.*, **191**, 501.
 SMITH, MAY (1922): *Industrial Fatigue Research Board, Report*, No. 22.
 VERNON, H. M. (1923): *Medical Research Council, Special Report*, No. 73, 121.

PART III. THE INFLUENCE OF COOLING POWER AND OF VARIABILITY OF AIR CURRENTS ON SENSATIONS OF AIR MOVEMENT

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Industrial Fatigue Research Board, assisted by C. G. WARNER.

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1. INTRODUCTION.

THE kata-thermometer was stated by Leonard Hill (1919, p. 13) to be 'an instrument designed primarily for the measurement of its own rate of cooling when its temperature approximates to that of the human body'. Nevertheless, it is often assumed that the cooling rates indicated by the instrument under various atmospheric conditions apply directly to the human body when exposed to the same conditions, though it differs so enormously from the kata in a number of ways. Firstly, in contrast to the naked bulb of the kata, the body is almost always clothed, and clothing greatly reduces the cooling power of moving air. For instance, it was shown by Hill and his colleagues (1920, p. 239) that a naked kata, when in still air, indicated a cooling power of 6.1, but when exposed to a mild breeze, it indicated one of 15. When the bulb was covered with a finger-stall of knitted wool, the cooling power was reduced to 4.8 in still air and to 7.0 in the mild breeze, so the moving air increased the cooling rate of the clothed kata only 46 per cent., as compared with an increase of 146 per cent. in the naked kata. When the kata bulb was covered with silk instead of wool, the mild breeze increased its cooling power 85 per cent., so it is obvious that the protective effect of clothing depends greatly on its quality. It might be thought that the clothing factor could be roughly corrected by using a kata covered with some standard thickness of cloth, but this is almost impossible owing to the fact that certain areas of the body, such as the face, are not covered at all, whilst other areas have very different thicknesses of clothing.

Again, the size of the human body, as compared with the kata bulb, has a very great influence on its cooling. Hill (1919, p. 48) compared the cooling rate of the kata with the heat loss of man and animals

by convection and radiation, as estimated by Lefèvre. The most complete set of data available relates to a pigling weighing 7.5 kgm. When in still air at a temperature of 5° to 20° C., the kata cooled 2.9 to 3.5 times faster than the pigling, but in an air current of 2.4 metres per sec. (472 ft. per min.) it cooled 5.9 to 12.1 times faster; i. e. it responded to the rapid air current two to three and a half times more than the pigling did. Presumably it would respond still more rapidly when contrasted with a naked man, the body weight of whom would be ten times that of the pigling. As Hill himself points out, large areas of the human body surface are sheltered from the wind when a quiet posture is maintained, and parts of the inner surface of the arms and thighs touch other parts, whilst the whole surface of the kata is fully exposed.

Another important difference depends on the evaporation of moisture from the surface of the body. When the skin is covered with visible perspiration, the cooling rate of the body is comparable to that of a wet kata-thermometer, but as a rule it is not comparable either to the dry or the wet kata, but to something between the two. Other differences between the response of the kata and the human body to temperature and air movement will be discussed further on.

How are these difficulties to be surmounted, and what conclusions can legitimately be drawn from the cooling power of the air as registered by the kata-thermometer, to its cooling power as it affects the human body? At the outset, we must clearly define what we are aiming at. We may desire to know (a) to what extent the air creates a sensation of coolness which is pleasant and comfortable for an individual who at one time may be sitting down and doing little or no muscular work, and at another time may be engaged on strenuous mechanical labour, or (b) to what extent the air, in virtue of its temperature and movement, is able to exert a physical cooling effect on the 70 kgm. or so of flesh and blood which constitute the human body. It seems desirable to obtain all the information we can in answer to both these questions, for they apply in different degrees according to the physical character of the work performed by the individuals subjected to the cooling air, (a) being most important to those engaged in light work, and (b) to those engaged in heavy work.

2. COOLING POWER IN RELATION TO SENSATIONS OF COMFORT.

Important information on cooling power in relation to sensations of comfort has recently been obtained at the Research Laboratory of the American Society of Heating and Ventilating Engineers, Pittsburgh. This laboratory contains two adjoining rooms, 8 × 17 × 10 ft., in which the temperature, humidity, and air movement can be controlled independently (Houghten and Yagloglou, 1923, 1924). The 'comfort zone' in still air was ascertained for a large number of individuals, who sat in these rooms in their ordinary clothing, under various conditions of temperature and humidity, whilst the effects of moving air were investigated by three subjects who passed backwards and forwards from one room to the other.

Each room contained a tunnel, $5 \times 7 \times 10$ ft., to one of which was fitted a bank of 20 electric fans, yielding an air current with a velocity of 50 to 700 ft. per minute. In one series of experiments the subjects were stripped to the waist (Yagloglou and Miller, 1924), and in a second series (1925) they were normally clothed. These investigators, and also Houghten and Yagloglou, showed that the sensation of comfort depends both on the wet bulb and the dry bulb temperatures of the air, and they ascertained the various combinations of temperature which created the same sensation of comfort. They combined them under the term of 'effective temperature', and their tables of data show that, for instance, an effective temperature of 64° would be given by air with a wet and dry bulb temperature of 64° , with a d.b. of 66.0° and a w.b. of 62.0° , a d.b. of 68.2° and a w.b. of 59.4° , a d.b. of 73.8° and a w.b. of 52.4° , and so on. From one of their charts we have determined the combinations of effective temperature and air velocity which gave equally comfortable conditions in men normally clothed. The data quoted relate to air

<i>Velocity of air current in feet per minute.</i>	<i>Temperature.</i>	<i>Cooling power.</i>
0	66.0°	4.8
100	68.3°	7.7
200	70.2°	9.1
300	71.8°	10.2
500	74.0°	11.5

saturated with moisture, so the effective temperatures given are likewise dry bulb temperatures. From them and from the air velocities the dry kata cooling power has been calculated, and it will be seen that it is very far from remaining constant. It rapidly rises as the velocity of the air current increases, and with normally clothed men exposed to air of 500 ft. velocity it is nearly $2\frac{1}{2}$ times greater than in still air. Supposing that the air velocity be kept steady (e.g. at 50 ft. per min., a value frequently observed in factories), and the humidity be changed, we still find great differences in cooling power. Thus Yagloglou and Miller found that equal comfort was experienced at the following temperatures by men stripped to the waist.

<i>Dry bulb temperature.</i>	<i>Wet bulb temperature.</i>	<i>Saturation of air with moisture.</i>	<i>Calculated cooling power.</i>
67.3°	67.3°	100%	6.6
69.1°	65.0°	80%	6.2
71.1°	61.9°	60%	5.7
73.4°	58.5°	40%	5.2
76.0°	53.9°	20%	4.6

At first sight these and other similar data suggest that the kathermometer is hopelessly at fault as an index of comfortable conditions for sedentary individuals and those engaged in very light work, but we shall see that this conclusion is erroneous, and that with certain allowances the kata probably yields as fair an index of comfort as is obtainable. The apparent conflict of evidence is due to the fact that comparisons of comfort made by the two-chamber method suffer from one very important disability, which

largely neutralizes their significance. *They take no account of acclimatization.* The average individual, under average conditions, is not in the habit of changing suddenly from rooms with high temperature and high air velocity to those with low temperature and low velocity, or vice versa. In most work rooms comparatively small changes of temperature are experienced from moment to moment, though as a rule the temperature gradually warms up 5° to 10° F. in the course of the morning. During this gradual rise the workers to some extent become acclimatized to the increasing temperature, and evidence in support of this statement is afforded by Houghten and Yagloglou. In determining the comfort zone, they sometimes started at too low a temperature for comfort and gradually raised it till it became comfortable or too warm, and at other times they reversed the conditions. Reading off the temperatures recorded in one of their diagrams, we found that on an average the comfortable effective temperature was 64·6° when approached from the cold side, and 65·5°, or nearly 1° higher, when approached from the warm side.

More marked than the diurnal changes of acclimatization are the seasonal changes. As the mean temperature of the air gradually rises on passage from winter to summer weather, each of us undergoes a gradual adaptation, and at the same time we put on thinner clothes. In consequence, we experience the same extent of comfort at a temperature several degrees higher than that observed in winter time. To take a rather extreme instance, one of us (H. M. V.) found (1923, p. 116) that when he exposed himself to very high temperatures for about three hours at a time on alternate days for a month, the maximum limit of wet bulb temperature that he could endure without a rapid rise of body temperature increased 6° F. His pulse and respiration rate became much less affected than at first, whilst his loss of sweat increased.

Acclimatization has the effect of diminishing the relative importance of the temperature factor of cooling power (as measured by kata-thermometer), and consequently, of increasing the relative importance of the air movement factor. The extent of this alteration can neither be measured nor predicted, so the only method open to us for estimating the significance of the cooling power of the kata in terms of human comfort is the very laborious one of empirical graduation. Systematic observations of this character are described below, whilst evidence relating to the parts played by air temperature, air movement and clothing in the cooling of the human body from its purely physical side, are described in Part IV of this Report.

3. SENSATIONS OF AIR MOVEMENT IN RELATION TO COOLING POWER.

In order to graduate the kata-thermometer empirically, we recorded our sensations of air movement systematically before each determination of cooling power, according to an agreed scale. At first we thought that a five-fold classification would be sufficient, and we designated the sensation of air movement experienced as being 'very stagnant', 'stagnant', 'medium', 'fresh' or 'very

fresh', but we often found that the sensation occupied some intermediate position, so we accordingly adopted the following more elaborate scheme :

<i>Sensation of air movement experienced.</i>	<i>Marks assigned.</i>
Very stagnant	0
Very stagnant to stagnant	1
Stagnant	2
Stagnant to medium	3
Medium	4
Medium to fresh	5
Fresh	6
Fresh to very fresh	7
Very fresh	8

For convenience of recording, we assigned 0 to 8 marks to the various classes, and as most of the observations to be described were made by two investigators (T. B. and C. G. W.) working conjointly, they noted down their sensations independently, and took a mean between the assigned values. The investigators made 229 observations during the summer (June to Sept.), and 203 observations during the winter (Jan. to Mar.), and the degrees of correspondence between their recorded sensations is shown in the Table :

<i>Difference in marks assigned.</i>	<i>Summer observations.</i>	<i>Winter observations.</i>
0	50%	71%
1	22%	20%
2	25%	7%
3	2%	2%
4	1%	0%

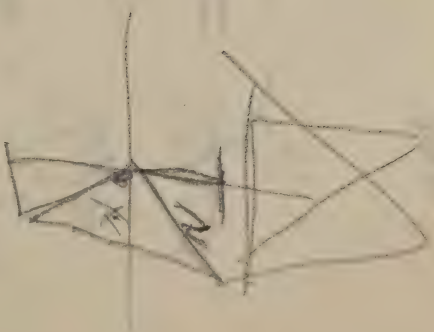
It will be seen that the investigators agreed exactly in their estimate in 50 per cent. of the summer observations and 71 per cent. of the winter observations, whilst they differed by two units or less in respectively 97 and 98 per cent. of the observations. The closer correspondence attained in the winter observations may be due to the fact that they were made subsequently to the summer observations, by which time the investigators had presumably acquired more skill in interpreting their sensations.

The observations were made at twelve different factories, and in order to test our method thoroughly, we varied the conditions as much as possible by turning on and off the ventilating and heating systems, and opening and shutting windows. Even then the extremes of air movement or lack of movement were experienced but seldom, as can be gathered from Table I. In addition to the combined observations, one investigator (C. G. W.) made 284 records of air sensation when he was engaged on routine kata-thermometer determinations under ordinary factory conditions, and it will be seen (cf. Table II) that his sensations were almost always confined to those ranging from stagnant to fresh (2 to 6 marks).

The mean dry kata cooling power observed varied from 3.9 to 7.9 in the summer observations, and from 5.2 to 8.9 in the winter ones. On an average, the cooling power was 1.1 units higher in the winter than the summer, and it may be said that, roughly speaking, in order to produce a given sensation of air movement in the winter

$$\int_0^{\pi} r^2 \cos \theta \, d\theta = a - a \sin \theta \Big|_0^{\pi}$$

$$-a \cos \theta + a \cos \theta \sin \theta \Big|_0^{\pi} \frac{a^3}{3} \Big|_0^{\pi}$$



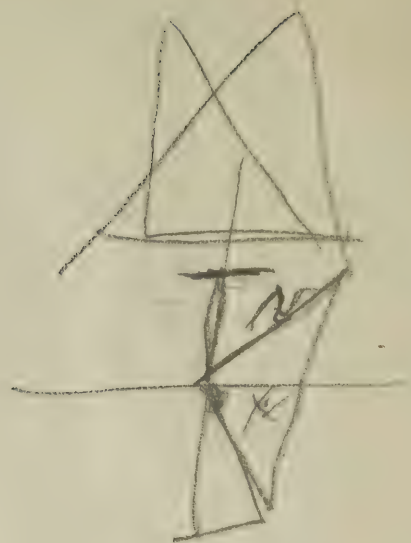
$$2 \int \int r^2 \sin \theta \, d\theta \, dx$$

$$\int r^2 \sin \theta \, d\theta = r^2 \int \sin \theta \, d\theta = -r^2 \cos \theta + f(r, \theta)$$

$$4 \int_0^{\pi/2} \int_0^{\pi} r \sin \theta \, d\theta \, dr = 0 \int_0^{\pi/2} \int_0^{\pi} r \sin \theta \, d\theta \, dr$$

$$\int_0^{\pi} \int_0^{a-a\sin\theta} r^2 \cos\theta \, dr \, d\theta$$

$$= a \cos^0 + a \cos\theta \sin\theta \left[\frac{r^3}{3} \right]_0^{\pi}$$



$$2 \int \int e^x \sin y \, dy \, dx$$

$$\int e^x \sin y \, dy = e^x \int \sin y \, dy = -e^x \cos y + f(x) + C$$

$$4 \int_0^{\frac{\pi}{2}} \int_0^{\sin\theta} r \, dr \, d\theta = 0 \int_0^{\sin\theta} \int_0^{\frac{\pi}{2}} r \, dr \, d\theta$$

$$\frac{1}{2} \sin\theta \Big|_0^{\frac{\pi}{2}} = 0 \int_0^{\sin\theta} \left[\frac{r^2}{2} \right]_0^{\frac{\pi}{2}} = \sin\theta \frac{r^2}{2} + f(\theta) + C$$

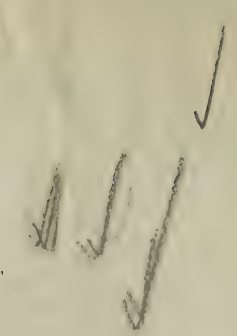
$$\frac{1}{2} \cdot \frac{\pi^2}{2} = \frac{\pi^2}{4}$$

$$\int_0^{\pi} \int_0^{\frac{\pi}{2}} r^2 \sin\theta \, dr \, d\theta \, d\phi$$

$$\frac{a^3}{3} \int_0^{\pi} \int_0^{\frac{\pi}{2}} \cos^3\theta \, d\theta \, d\phi = \frac{a^3}{3} \cdot \frac{\cos^4}{4} = \frac{a^3}{3} \cdot \frac{2}{3}$$

$$\begin{array}{r} 73.2 \\ 69.8 \\ \hline 3.4 \end{array} \quad 100'$$

$$\begin{array}{r} 69.8 \\ 66.4 \\ \hline 3.4 \end{array}$$



$$\frac{y^2}{x} = 50$$

$$\frac{y^2}{x} = 2y \bar{x}' dy + -y^2 dx$$

$$\frac{2y}{-y^2 x} = \frac{L_1}{dx} = \frac{2y}{x^2} = \frac{2}{x^2}$$

100'

$$\frac{2}{(1)} = 2$$

$$\frac{2}{1(2)} = 1$$

$$\frac{2}{(1)(3)} = .66\frac{2}{3}$$

$$\frac{2}{(1)(4)} = .50$$

$$\frac{2}{(1)(5)} = .40$$

$$\frac{2}{(1)(6)} = .33\frac{1}{3}$$

$$\frac{2}{(1)(7)} = .28\frac{2}{7}$$

$$\frac{2}{(1)(8)} = .25$$

$$\frac{2}{(1)(9)} = .22\frac{2}{9}$$

$$\frac{2}{(1)(10)} = .20$$



$$\frac{74.2}{2.5} = 29.68$$

$$\frac{100}{100} = 1$$

300'

600'

900'

1000'

$$\frac{1}{2} \int_0^{\pi} \sin^2 \theta d\theta$$

$$= \frac{1}{2} \int_0^{\pi} (1 - \cos^2 \theta) d\theta$$

$$= \frac{1}{2} \left[\theta - \frac{\sin^3 \theta}{3} \right]_0^{\pi}$$

$$= \frac{1}{2} \left[\pi - \frac{\sin^3 \pi}{3} - \left(0 - \frac{\sin^3 0}{3} \right) \right]$$

$$= \frac{\pi}{2}$$

$$\int_0^{\pi} \frac{1}{2} \sin^2 \theta d\theta$$

$$= \frac{\pi}{2}$$

$$\frac{\pi}{2}$$

$$\int_0^{\pi} \cos^3 \theta d\theta = \frac{\theta}{3} - \frac{\sin^3 \theta}{3} \Big|_0^{\pi} = \frac{\pi}{3} - \frac{\sin^3 \pi}{3} - \left(\frac{0}{3} - \frac{\sin^3 0}{3} \right) = \frac{\pi}{3}$$

$$\frac{y}{x} = x^{-1} y$$

$$x^{-2} y dx = x^{-1} dy = 0$$

$$\frac{y}{x^2 x} = \frac{1}{x^3} = \frac{dy}{dx} \quad x = 30^\circ$$

$$\frac{1}{x^3}$$

$$x = 40^\circ$$

$$x = 50^\circ$$

$$x = 60^\circ$$

$$\frac{1}{x^3 y} = c$$

$$x^3 y = 1$$

$$y = \frac{1}{x^3}$$

$$y = \frac{1}{9}$$

$$y = \frac{1}{16}$$

$$y = \frac{1}{25}$$

$$y = \frac{1}{36}$$

The greater the variation between the wet & dry bulb the ~~greater~~ dryer the atmosphere.

If the two then be compared degree for degree and a line drawn connecting those pts the horizontal line will give the effective normal reading Scale.

it was necessary for the air to have a cooling power one unit higher than that required in the summer. This difference of standard was chiefly due to temperature, which was about 7° F. higher in the summer than in the winter, though its effects were to some extent neutralized by the increased air velocity, which was usually about 9 ft. per minute greater in the summer. It will be seen that as the sensation of air movement experienced progressed through each stage from very stagnant to very fresh, the cooling power rose steadily in correspondence, but the two components on which the cooling power depends showed no such uniformity of rise. In the summer observations the air velocity was nearly constant whether the sensation experienced was 0, 1, 2, or 3, and the increasing sensation was due almost entirely to fall of temperature, for this declined gradually from 75.6° to 68.9° . On the other hand, the temperature was constant when the sensation experienced ranged from 6 to 8, and the increasing sensation of air movement was due entirely to the air velocity, which gradually rose from 44 ft. per min. to 82 ft. This series of summer observations shows very strikingly, therefore, that the sensation of air movement experienced cannot be measured in terms either of temperature or of air velocity, but needs a combination of the two, such as that given by the cooling power of the kata-thermometer. The winter observations show a fairly steady velocity with sensations of 0, 1, 2, and 3, and only a slightly increased velocity with sensations of 4 and 5, whilst the air temperature shows a considerable fall. On the other hand, a steady temperature was observed with sensations 7 and 8, but a rapid rise of air velocity.

The correlation between sensation of air movement and the kata observations has been determined by estimating the correlation ratios. The correlation coefficient is not applicable, because the air sensation variable is not a quantitative one, and we have no means of determining whether the association is strictly linear. Were it linear, the correlation ratio (η) would be identical with the correlation coefficient (r), but under the circumstances it is somewhat larger. Still, the data adduced show that there is a high correlation between air sensation and cooling power both in summer and winter. There is also a high correlation between air sensation and temperature

<i>Correlation ratio of</i>	<i>Summer observations.</i>	<i>Winter observations.</i>
Cooling power on air sensation . . .	0.703 ± 0.023	0.790 ± 0.018
Temperature " " . . .	0.531 ± 0.032	0.740 ± 0.021
Air velocity " " . . .	0.569 ± 0.030	0.381 ± 0.041

in the winter observations, but a somewhat low correlation with air velocity. In the summer observations the correlation is fairly high both with temperature and air velocity.

The other set of observations on air sensation and cooling power, which was made by one investigator in winter time, is recorded in Table II. Ignoring the observations made with air sensations of 0, 1, 7, and 8, because of their infrequency, we see that the remainder correspond well with the combined observations of the two investigators, which were made under more variable atmospheric conditions. They therefore help to confirm the accuracy of the estimates of air sensation made. However, as might be predicted, the correlation

TABLE II. *Routine Observations by One Investigator.*

<i>Sensation of air movement experienced.</i>	<i>No. of observations.</i>	<i>Cooling power.</i>	<i>Temperature.</i>	<i>Air velocity in feet.</i>	<i>Difference from combined winter observations.</i>		
					<i>Cooling power.</i>	<i>Temperature.</i>	<i>Air velocity.</i>
Very stagnant . . . (0)	3	(4.5)	(73.3°)	(28)	—	—	—
Very stagnant to stagnant (1)	1	(6.2)	(71.1°)	(69)	—	—	—
Stagnant . . . (2)	58	5.9	64.5°	23	+ 0.1	— 0.2°	+ 2
Stagnant to medium . (3)	21	6.3	62.8°	24	+ 0.2	— 1.1°	0
Medium . . . (4)	129	6.7	61.4°	26	+ 0.1	— 0.7°	0
Medium to fresh . . (5)	20	7.3	61.2°	38	+ 0.2	+ 0.9°	+ 9
Fresh . . . (6)	48	7.3	60.4°	33	— 0.4	+ 1.1°	+ 3
Fresh to very fresh . (7)	2	(10.6)	(54.4°)	(79)	—	—	—
Very fresh . . . (8)	2	(10.6)	(60.4°)	(123)	—	—	—

TABLE III. *Temperature and Velocity of Air causing a Medium Sensation of Air Movement.*

	<i>Classified according to velocity.</i>				<i>Classified according to temperature.</i>			
	<i>No. of observations.</i>	<i>Velocity in feet per min.</i>	<i>Temperature.</i>	<i>Cooling power.</i>	<i>No. of observations.</i>	<i>Temperature.</i>	<i>Velocity.</i>	<i>Cooling power.</i>
Summer observations	5	16 (19 or less)	63.0°	5.9	10	62.7° (63.9° or less)	30	6.7
	17	24 (20 to 29)	66.0°	5.8	14	65.1° (64.0° to 65.9°)	32	6.3
	19	34 (30 to 39)	68.1°	5.8	11	66.9° (66.0° to 67.9°)	30	5.9
	14	44 (40 to 49)	70.1°	5.7	14	69.0° (68.0° to 69.9°)	35	5.6
	7	61 (50 or more)	72.8°	5.6	13	75.5° (70.0° or more)	48	4.6
Winter observations	27	16 (19 or less)	61.2°	6.2	13	58.4° (59.9° or less)	23	7.3
	32	24 (20 to 29)	62.0°	6.6	42	61.6° (60.0° to 62.9°)	22	6.5
	14	34 (30 to 39)	62.9°	6.9	21	64.7° (63.0° to 65.9°)	32	6.4
	6	49 (40 or more)	64.0°	7.3	3	66.1° (66.0° or more)	30	6.0

ratios were not so high as before. That of cooling power on air sensation was $.587 \pm .026$; that of temperature on air sensation was $.480 \pm .031$; whilst that of air velocity on air sensation was $.294 \pm .037$.

Though the observations on temperature and velocity in relation to sensations or air movement, when taken as a whole, strongly support the claims of the kata-thermometer as an indicator of cooling power, they do not yield such favourable evidence when taken in individual groups. Consider, for instance, those observations producing a 'medium' sensation of air movement, or what may probably be regarded as comparable to the 'comfortable' conditions investigated by the two-chamber method in America. In order to increase the small number of data available, we have added to those causing a medium sensation (4 marks) such as were awarded $3\frac{1}{2}$ or $4\frac{1}{2}$ marks, and this plan gave us altogether 62 summer observations and 79 winter ones. In Table III we have classified

these observations in four or five groups, according to velocity and to temperature. We see that in the summer data classified according to velocity, the corresponding mean temperature rose regularly as the mean velocity rose, and in consequence the cooling power remained almost steady throughout, as would be expected. When, however, the same data were classified according to temperature, the corresponding mean velocity did not rise sufficiently rapidly, and in consequence the cooling power fell considerably. However, these results, so far from supporting the observations of the American investigators, appear to indicate that the (acclimatized) human body was excessively sensitive to small variations of air velocity. The winter data, when classified according to velocity, show a gradual rise of cooling power (a result supporting the American observations), but when classified according to temperature they show

TABLE IV. *Seasonal Variation of Cooling Power in Relation to Air Sensations.*

<i>Sensation of air movement experienced.</i>	<i>Mean cooling powers observed in</i>				
	<i>June.</i>	<i>July-Aug.</i>	<i>Sept.</i>	<i>Jan.</i>	<i>Feb.-Mar.</i>
Very stagnant and v. stagnant-stagnant (0, 1)	3.7	4.7	4.8	5.7	5.1
Stagnant and stagnant-medium . . . (2, 3)	5.1	4.8	5.5	5.9	6.2
Medium (4)	5.2	6.1	6.1	6.6	6.5
Medium-fresh and fresh . . . (5, 6)	6.1	6.6	6.6	7.3	7.3
Fresh-very fresh and very fresh . . (7, 8)	7.1	7.3	7.5	7.9	9.2
Mean	5.4	5.9	6.1	6.7	6.9
Mean room temperature	70.7°	67.6°	66.1°	61.6°	61.4°
Mean outdoor temperature	64.4°	62.1°	60.2°	41.7°	41.0°
Number of observations	89	76	64	99	104

a gradual fall of cooling power, as in the summer data, and are therefore opposed to the American observations. If the two sets of data are combined and averaged, they show a cooling power which is practically constant throughout (i.e. 6.7, 6.5, 6.6, 6.6). The interpretation of this result is doubtful, but in any case it does not lend support to the American observations. Probably it is due chiefly to the difficulties of the investigators in estimating the sensation of air movement, for their estimates would often be influenced to some extent by their immediately preceding experiences.

4. THE ACCLIMATIZATION FACTOR.

The differences observed between the summer and winter results are partly due to differences in the clothing worn by the investigators, but chiefly to acclimatization. This conclusion is strikingly supported by splitting up the observations into smaller groups, and averaging them. It will be seen from Table IV that the summer observations were split up into three groups, according as they were made in June, July-August, or September, whilst the winter ones were split up into two groups, according as they were made in January, or February-

March. The air sensation classes have been reduced from nine to five, and it will be seen that the mean cooling powers associated with them vary in fairly regular sequence. The means of the cooling powers in each monthly group show a linear relationship to the mean indoor temperatures observed at the time the cooling power was ascertained; as can be judged from Fig. 1. If the line joining the ascertained points is continued in both directions, it is found that the cooling power corresponding to an air temperature of 60° F. is almost exactly 7.0,

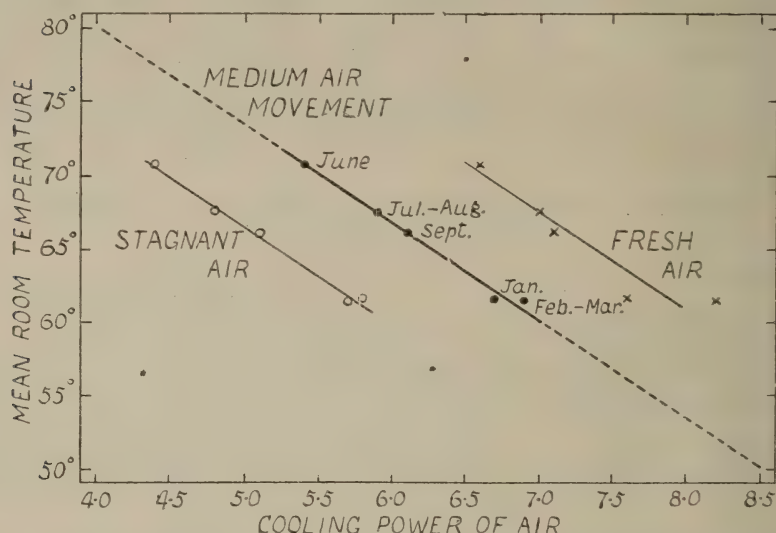


FIG. 1. Seasonal variation of cooling power in relation to sensation of air movement.

with a correction of ± 0.15 for each $^{\circ}$ F. below or above this temperature. Thus :

At 80°	the cooling power is	4.0 (or $7.0 - 0.15 \times 20$)
" 70°	" "	5.5 (or $7.0 - 0.15 \times 10$)
" 60°	" "	7.0
" 50°	" "	8.5 (or $7.0 + 0.15 \times 10$)

It will be seen from Table IV that these mean monthly cooling powers correspond closely with the cooling powers observed when the sensation of air movement was judged by the investigators to be medium (the differences being only $+0.2$, -0.2 , ± 0.0 , $+0.1$ and $+0.4$ respectively), so they may probably be regarded as a fairly reliable index of the average kata cooling power required to produce a moderately comfortable sensation of air movement at various times of the year. We may assume that the investigators were at all periods moderately well acclimatized to the particular air temperatures they had been subjected to in the course of their daily round of work and leisure. It was not feasible to ascertain these temperatures, but probably the mean factory temperatures recorded in Table IV are quite a good index, as the investigators were working in the factories for about seven hours each day. A second index was obtained by ascertaining the mean outdoor temperature during each day when observa-

tions were made, and averaging the means. We could not easily obtain temperature records at each of the five towns where we made our observations (Leicester, Norwich, Hull, Leeds, Kettering), so in default of them we quote the means of the temperatures recorded at the Kew Observatory, London, at 7 a.m., 1 p.m., and 6 p.m. (Greenwich time). It will be seen that they fall in orderly sequence as we pass from June to February-March, just as do the indoor temperatures observed. Supposing that we take for our standard of air sensation a feeling of freshness or a feeling of stagnancy, we still observe a roughly linear relationship between sensation and air temperature. Thus we have plotted in Fig. 1 the mean cooling powers observed in the various monthly periods for sensations 0, 1, 2, and 3 on the one hand, and for sensations 5, 6, 7, and 8 on the other. It will be seen that the observed points agree fairly well with the lines drawn through them, and that these lines are parallel with the intermediate line.

It must be realized that the cooling powers associated with various mean indoor temperatures virtually depend on the sensations of two investigators only, though the third investigator, when he took part in the observations, was in close agreement with the other two. It is necessary that similar observations be made by a number of other investigators before the cooling power corresponding to a given sensation of air movement can be regarded as definitely fixed, but in any case we have proved the importance of regarding cooling power, in relation to comfort, as a variable depending on acclimatization, and not as a fixed quantity. The figures quoted above suggest that the cooling power of 6, which Leonard Hill has adduced as the minimum requirement for workers engaged in sedentary occupations, holds only for an air temperature of about 64° to 67° , for this range would be equivalent, according to our data, to an air sensation of 3 to 4 (i. e. stagnant-medium to medium). On the other hand, in summer weather a cooling power of 5 would be reasonable, whilst in winter weather it might rise to 7 or more. It is true that the mean cooling power observed ranged only from 5.4 to 6.9, but the summer (1924) was a very cool one, and the winter (1925) a mild one.

5. SENSATIONS OF AIR MOVEMENT IN RELATION TO VARIABILITY OF AIR CURRENTS.

It is generally supposed that variable air currents have a greater cooling effect than steady currents, though no definite proof of this hypothesis has been adduced. By the use of our hot-wire anemometer we were able to obtain a direct measure of the velocity of the air currents at as brief intervals as we could read the galvanometer, and thereby calculate their variability. At first it was our custom to read the galvanometer at two-second intervals, but this speed needed the co-operation of two investigators, one to call out the reading, and the other to note it down. Subsequently we read the instrument at $2\frac{1}{2}$ sec. intervals, which gave time for a single investigator to read and note down the deviation. Meanwhile the second investigator was synchronously reading a second galvanometer attached to the thermopile (cf. Part I of this Report). We generally read the instru-

ments for five minute periods, and thereby obtained 120 readings. The variability of the air velocity was determined by calculating the *mean variation* of the readings on the average reading, and converting both the average and the mean variation into terms of actual velocity.

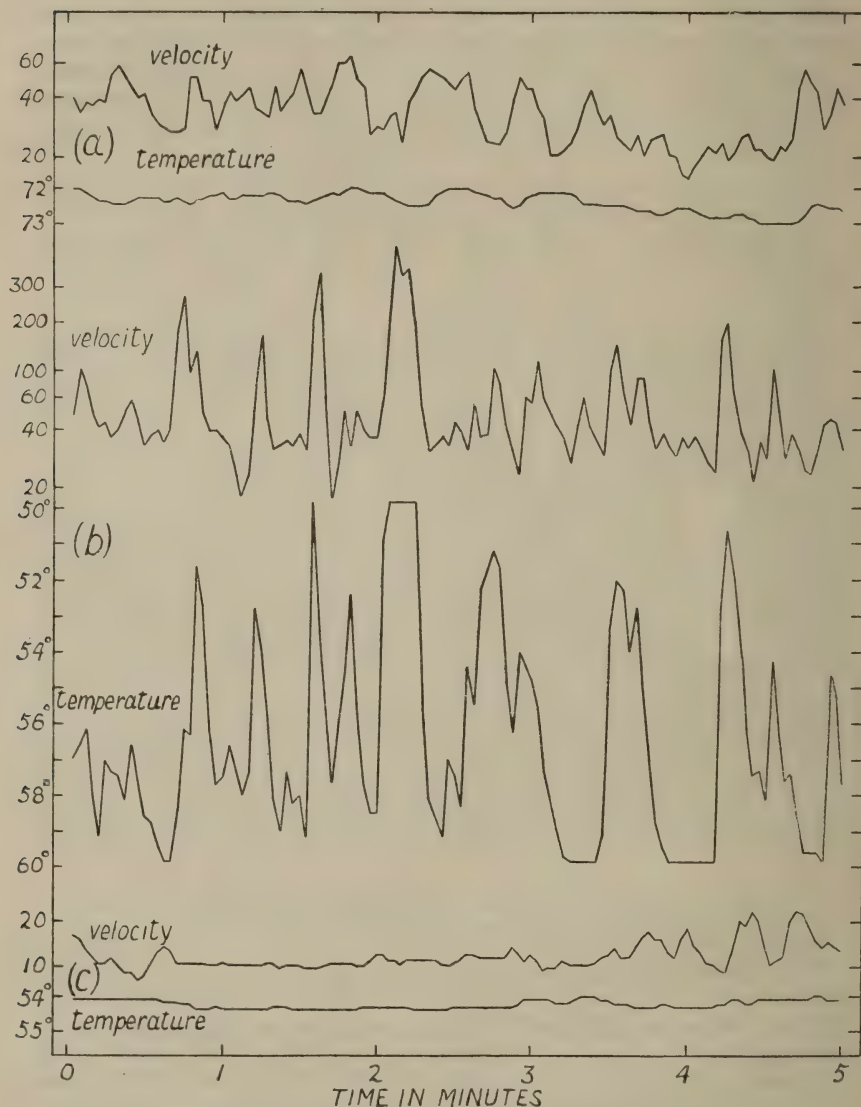


FIG. 2. Various degrees of oscillation in air velocity and temperature.

The converted mean variation was then calculated as a *percentage* on the corresponding velocity, and it is expressed in this form in all the data to be described. The mean variation of the thermopile readings was likewise calculated, and converted into terms of temperature. Thus a mean variation of 0.4° means that the temperature showed an

average oscillation of 0.4° F. on either side of the mean temperature of the room at the time the observations were made.

As might be expected, the oscillations of air velocity and air temperature were exceedingly variable, and a few samples are given here, whilst other samples are reproduced in the next section. A fairly average pair of curves (obtained in summer) is shown in Fig. 2 (a), the mean variation of the air velocity being 25 per cent., whilst the mean variation of the temperature was 0.21° . It will be seen that the two curves show some correspondence, for on several occasions the temperature of the air fell and rose when the velocity rose and fell. This was due to weak draughts of cooler air entering from open windows. A greater correspondence is shown in the second pair of curves, which were obtained in winter time by placing the hot-wire detector 5 ft. from an open window. Both the curves have much greater oscillations than the average, for the mean variation of the velocity was 56 per cent., and that of the temperature, 2.37° . The third pair of curves show smaller oscillations than the average, the mean variation of the velocity being 18 per cent., and of the temperature, 0.11° . There is little or no correspondence between the two curves, and the same thing is true of the pairs of curves shown in Fig. 3.

The relationship of variability of air currents to sensation of air movement was tested systematically in the series of cooling power observations previously described. In each of these observations the dry kata cooling power was determined twice, then the hot-wire and the thermopile galvanometers were read for five minutes, and finally two more observations of cooling power were made. The mean results are recorded in Table V, and it will be seen that, in the summer observations, the mean variation in air velocity was almost constant at all sensations of air movement ranging from very stagnant to medium (0 to 4), as it varied only from 26 to 29 per cent. In the winter observations it was almost as steady over the same range of air sensation. With fresher air currents it showed a definite increase, both in summer and winter, till it reached its maximum in very fresh air, and amounted to 39 and 42 per cent. respectively. It seems probable, therefore, that the more variable an air current, the more does it tend to provoke a sensation of air movement.

It will be seen in Table V that the velocity ascertained by the hot-wire galvanometer was distinctly greater than that ascertained by kata-thermometer, the ratio of the one to the other being usually as 1.2 to 1 in the summer, and as 1.1 to 1 in the winter. The reason of this difference has been indicated in Part II of this Report, where it is shown that the kata does not respond to vertical air currents nearly so well as the hot-wire anemometer. These vertical currents are probably more powerful in summer than in winter, owing to the entry of descending currents of cool air through open skylights and windows, and for this reason the summer values show the greatest divergence.

In the summer observations the oscillations of temperature were fairly steady at all degrees of air sensation, but it is necessary to point out that the values recorded apply only to the last half of the summer observations made, the thermopile not being in working order at first.

TABLE V. *Variations of Air Velocity and Temperature in Relation to Sensations of Air Movement.*

<i>Sensation of air movement experienced.</i>	<i>Summer observations.</i>					<i>Winter observations.</i>				
	<i>Velocity in ft. per min.</i>			<i>Mean variation of</i>		<i>Velocity in ft. per min.</i>			<i>Mean variation of</i>	
				<i>velocity</i>	<i>temper-</i>				<i>velocity</i>	<i>ature.</i>
	<i>Kata.</i>	<i>Gale.</i>	<i>Gale./Kata.</i>	(%).	ature.	<i>Kata.</i>	<i>Gale.</i>	<i>Gale./Kata.</i>	(%).	ature.
Very stagnant . . . (0)	27	38	1.4	26	0.27°	24	25	1.0	28	0.33°
Very stagnant to stagnant (1)	27	35	1.3	27	0.19°	18	17	0.9	29	0.23°
Stagnant . . . (2)	30	35	1.2	28	0.26°	21	23	1.1	26	0.26°
Stagnant to medium (3)	29	35	1.2	29	0.24°	24	24	1.0	24	0.32°
Medium . . . (4)	35	41	1.2	29	0.20°	26	28	1.1	27	0.30°
Medium to fresh . . (5)	43	52	1.2	36	0.21°	29	28	1.0	33	0.32°
Fresh . . . (6)	44	53	1.2	38	0.22°	36	43	1.2	32	0.52°
Fresh to very fresh . (7)	50	60	1.2	32	0.25°	29	30	1.0	35	0.42°
Very fresh . . . (8)	82	101	1.2	39	0.18°	45	59	1.3	42	0.90°
Mean	41	50	1.2	32	0.22°	28	31	1.1	31	0.40°

However, the thermopile was employed for the whole of the winter observations, and we see in their case that though the mean variation was fairly steady with air sensations of 0 to 5, it rapidly increased in fresh air, and attained a maximum of 0.9° in very fresh air.

The dependence of sensations of air movement on oscillations in air velocity is not really settled by the data recorded in Table V, for it may happen that an increasing oscillation is naturally associated with increased velocity of air current, and that the effect produced on sensation is dependent only on the increased velocity, and not on its oscillations. In order to obtain further evidence, we have reclassified our data according to air velocity, and it will be seen from Table VI that increasing air velocities do not have increasing oscillations consistently associated with them. In the summer observations the mean variation in velocity remained nearly constant for all air velocities up to 50 ft. per min., and in the winter observations it remained nearly constant for all velocities up to 40 ft. per min. We have accordingly taken these two groups of observations (which were respectively 156 and 169 in number), and re-grouped them according as the mean variation in velocity was under 20 per cent., 20 to 24 per cent., and so on. From Table VII it will be seen that the sensation of air movement experienced rose gradually as the oscillations in velocity increased, being 3.6 or 3.7 with the least oscillation, and 4.4 or 4.6 with the greatest. In the summer observations the mean air velocity and the cooling power remained steady throughout, so presumably the whole of the increase in air sensation experienced must have been due to the increased oscillations. In the winter observations, however, there was a rise of cooling power, which must have been responsible for a part of the increased air sensation.

The correlation ratio between the velocity oscillations and air sensation was found to be $0.365 \pm .039$ in summer, and $0.418 \pm .039$ in winter. When, however, the ratios were confined to the observations having an air velocity of less than 50 ft. per min. in summer and 40 ft. in winter, the ratios fell to $0.255 \pm .051$ and $0.371 \pm .045$ respectively. Hence the available evidence appears to indicate that oscillations of air velocity have only a moderate effect on sensations of air movement. They are less effective than the actual speed of the air current, for the correlation ratio of air velocity (as determined by hot-wire anemometer) on air sensation was $0.508 \pm .033$ in summer and $0.405 \pm .040$ in winter.

The correlation ratio of temperature oscillations on air sensation (for winter observations) was $0.422 \pm .039$, but it is very doubtful if this figure can be accepted as valid evidence that the oscillations had an influence on sensation. It will be seen in Table VI that the temperature oscillations increased steadily as the air velocity increased, and this association may be the explanation of the moderately high correlation ratio observed. Still, there can be no doubt that temperature oscillations do produce some effect on air sensation. They must act in the same way as velocity oscillations, and stimulate the cold and hot spots of the skin, though perhaps only in small degree.

The correlation ratio of *wet bulb* temperature on air sensation (for winter observations) was found to be $0.739 \pm .022$, or almost exactly the same as that previously recorded for dry bulb tempera-

TABLE VI. *Variations of Air Velocity in Relation to Actual Velocity.*

Air velocity in feet per minute.	Summer observations.					Winter observations.				
	Average velocity.	Mean variation in velocity (%).	Air sensation.	Temperature.	No. of observations.	Mean velocity.	Mean variation in velocity (%).	Air sensation.	Temperature.	No. of observations.
Under 20	17	27	2.9	65.2°	14	16	27	3.8	61.0°	70
20 to 29	25	27	3.4	66.6°	46	25	29	4.0	62.1°	59
30 to 39	35	27	3.9	67.6°	55	34	28	4.4	61.2°	40
40 to 49	44	28	4.8	68.0°	41	44	34	5.1	61.7°	20
50 to 59	54	35	4.4	70.7°	23	62	38	5.8	60.3°	8
60 to 69	64	41	5.2	68.5°	13					
70 to 79	74	49	4.8	70.9°	14	130	40	6.0	61.7°	6
80 to 89	84	54	5.7	71.3°	10					
90 to 129	112	53	5.3	71.7°	8					
130 or more	164	36	7.4	66.5°	5					

TABLE VII. *Sensation of Air Movement in Relation to Variations in Velocity.*

Range of mean variation in velocity.	Summer observations.					Winter observations.						
	Average M.V. (%).	Velocity (galv.).	Air sensa- tion.	Cooling power.	Temper- ature.	No. of observa- tions.	Average M.V. (%).	Velocity (galv.).	Air sensa- tion.	Cooling power.	Temper- ature.	No. of observa- tions.
Under 19%	17	33	3.7	5.7	67.1°	13	16	20	3.6	6.4	61.7°	21
20 to 24%	23	31	3.6	5.8	66.9°	42	22	24	3.8	6.5	62.2°	43
25 to 29%	27	33	3.7	5.6	68.0°	57	27	24	3.8	6.5	61.8°	41
30 to 39%	33	35	4.4	5.8	67.5°	37	34	25	4.4	6.8	61.0°	46
40% or more	43	34	4.4	5.7	67.0°	7	45	22	4.6	7.1	59.6°	18

ture on air sensation. Merely for convenience, the mean wet bulb temperatures associated with the various classes of air sensation are recorded in Table V.

6. INFLUENCE OF VENTILATION ON THE MAGNITUDE AND VARIABILITY OF AIR CURRENTS

It was thought to be of interest to utilize the hot-wire anemometer for observations on certain ventilation systems, more particularly with a view to ascertaining whether the magnitude and variability of the air currents induced could not be improved upon by some scheme of intermittent ventilation. We found that the results obtained were very irregular, so we systematically repeated them a number of times and took means.

The most complete series of observations was made at a factory with four workrooms, one above the other, and all ventilated by the same plenum system. These rooms were 120×54 feet in area, and the main plenum trunk distributed air equally to all of them, but the ventilation could be shut off from each room separately, and if desired, the whole force of the ventilation fan be confined to one room. This did not mean that it discharged four times more air than usual into the room, for owing to the increased resistance the actual increase was found by vane anemometer to amount only to 27-52 per cent.

In Table VIII are recorded the means of the summer and winter observations made in two of the three rooms. In making the observations, the recording instruments were placed at a number of different spots in the rooms at head level so as to give an average result. It will be seen that in the summer the turning on of the fan increased the sensation of air movement considerably (i. e. from 4.0 to 5.8), for the full force of the fan caused a doubling of the air velocity, and a small increase in the oscillations. In winter, however, the turning on of the full force of the fan reduced the air sensation experienced from 5.0 to 1.9 (i. e. from fresh-medium to stagnant), because it drove overheated air into the room, and thereby raised the temperature rather suddenly from 60.0° to 66.3° . There was a small increase of air velocity, but this could not compensate for the rise of temperature. It will be noted that the air sensation was reduced more than might have been expected from the change in kata cooling power. This is because it occurred suddenly, and gave no opportunity for acclimatization. In Fig. 3 we reproduce some sample records, and it will be seen that the temperature oscillation was very small in the summer and was practically unaffected by the fan, whilst in the winter it was larger, and was much increased by the fan. There was very little correspondence between the oscillations of velocity and those of temperature.

Observations on plenum ventilation systems were made at five other factories, and we found that when the ventilation current was turned on the small increase of air velocity induced was generally accompanied by a small decrease in its relative variability. On an average the velocity was increased from 36 ft. to 41 ft. per

min. in summer, and from 27 ft. to 32 ft. in winter, whilst the mean variation was reduced from 30 to 29 per cent. in the summer, and from 31 to 29 per cent. in the winter. Apparently, therefore, there is but

TABLE VIII. *Effects of Continuous Plenum Ventilation.*

	Air sensation.	Temperature.	Cooling power.	Air velocity shown by		Mean variation of velocity (%)	Mean variation of temperature.	No. of observations.
				kata.	galv.			
Summer observations	Fan off . . .	64.4°	6.1	24	24	28	0.12°	15
	Usual fan on . .	64.9°	6.3	31	33	26	0.16°	15
	Full fan on . . .	65.8°	6.7	45	50	33	0.13°	15
Winter observations	Fan off . . .	60.0°	7.1	26	27	33	0.42°	4
	Usual fan on . . .	61.6°	6.7	25	32	31	0.74°	4
	Full fan on . . .	66.3°	6.0	31	31	29	0.66°	4

little scope for effecting much improvement in the air movement induced by continuous plenum systems, so series of experiments were carried out on the effects of making the plenum ventilation *intermittent*. The air current to the rooms previously mentioned

could be shut off and turned on instantaneously by means of a baffle in the main trunk, and we made series of observations in which the current was alternately turned on for $\frac{1}{2}$ min., and off for 1 or $1\frac{1}{2}$ min.

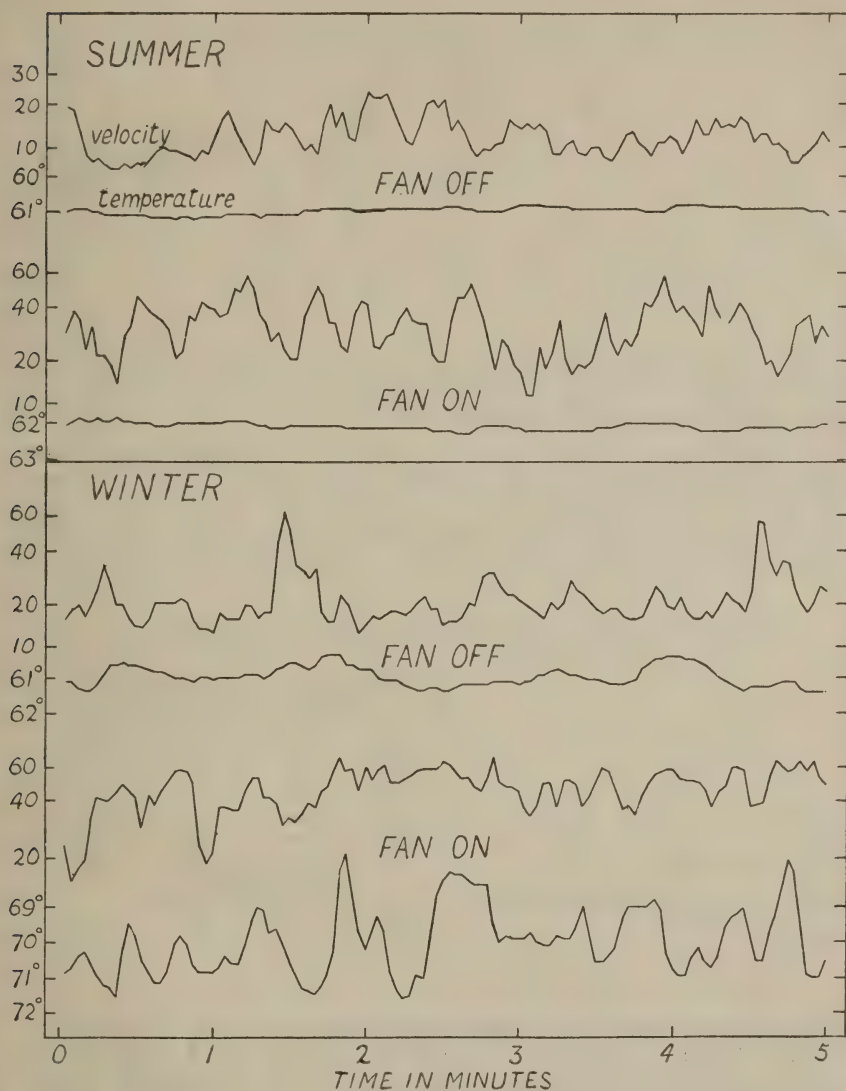


FIG. 3. Effect of plenum ventilation on oscillations of air velocity and temperature.

We determined the oscillations of velocity for 5 minutes with the fan off, for 5 min. with it on, and for 10 min. with it intermittent, the order of experiment being changed in each series. Observations were made in the two rooms mentioned with the full force of fan, and in another room with the usual fan.

In Table IX are recorded the means of 20 observations made under each set of conditions in winter time, and it will be seen that the intermittent fan had very little effect in increasing the air velocity, though it increased its mean variation from 26 per cent. to 32 per cent.

TABLE IX. *Effects of Intermittent Plenum Ventilation.*

	<i>Air sensa- tion.</i>	<i>Air velocity.</i>	<i>Mean varia- tion in velocity (%).</i>	<i>Temper- ature.</i>	<i>Calcu- lated cooling power.</i>	<i>No. of observa- tions.</i>
Fan off	4.1	23	26	62.0°	6.4	20
Fan on continuously	3.8	29	26	64.3°	6.2	20
Fan on $\frac{1}{2}$ min., off $1\frac{1}{2}$ min.	4.1	23	32	61.8°	6.4	20
„ $\frac{1}{2}$ „ „ 1 „	4.3	25	32	62.0°	6.5	20

This increase appeared, in the case of the $\frac{1}{2} : 1$ min. ventilation, to raise the sensation of air movement slightly (i. e. from 4.1 to 4.3), but the effect is scarcely a significant one.

A number of other observations were made in which no note was taken of the sensation of air movement experienced, and altogether 36 sets of observations were made with the $\frac{1}{2} : 1\frac{1}{2}$ min. intermittency, and 29 with the $\frac{1}{2} : 1$ min. intermittency. The mean results are recorded in Table X, and also the expected velocities and mean

TABLE X. *Effects of Intermittent Plenum Ventilation.*

	<i>With $\frac{1}{2} : 1\frac{1}{2}$ min. intermittency.</i>		<i>With $\frac{1}{2} : 1$ min. intermittency.</i>	
	<i>Air velocity. ft.</i>	<i>Mean variation. %</i>	<i>Air velocity. ft.</i>	<i>Mean variation. %</i>
Fan off	22.5	25.8	22.4	25.0
Fan on	27.3	26.7	28.2	26.6
Fan intermittent	23.6	31.5	24.7	33.1
Calculated velocity and M.V. for inter- mittent ventilation	23.7	26.0	24.3	25.5
Difference	-0.1	+5.5	+0.4	+7.6

variations calculated on a proportionate basis from the ' fan off ' and ' fan on ' data. It will be seen that the velocity found in the intermittent observations closely corresponded with the theoretical, whilst the oscillations of velocity were 21 to 30 per cent. greater than the theoretical. Hence it follows, as would naturally be expected, that intermittency of ventilation does materially increase the oscillations of velocity, and thereby induces a moderate increase in the sensation of air movement experienced. However, it must be admitted that the results obtained are rather disappointing, as the first observations made gave much more striking results. This was owing to the favourable positions selected for the hot-wire detector, and when it

was moved to other positions so as to yield a fair average result, the considerable improvement was no longer maintained.

If an intermittent system of ventilation were adopted, the intermittency would usually take the form of turning a motor on and off at regular intervals, rather than by turning baffles. The motor would take some seconds to gain and lose speed, and on that account the intermittency would not be so sudden. However, the effect is quite

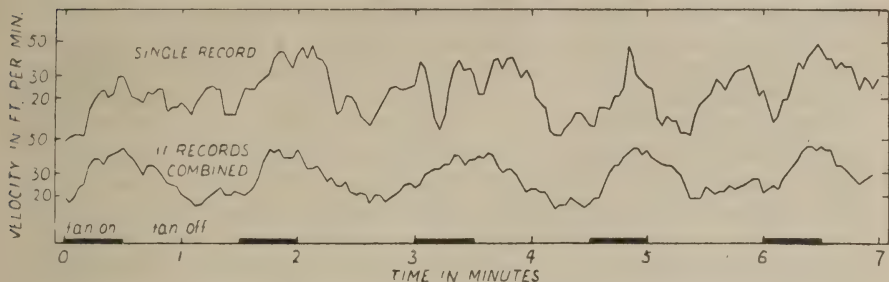


FIG. 4. Effect of intermittent ventilation on oscillations of air velocity.

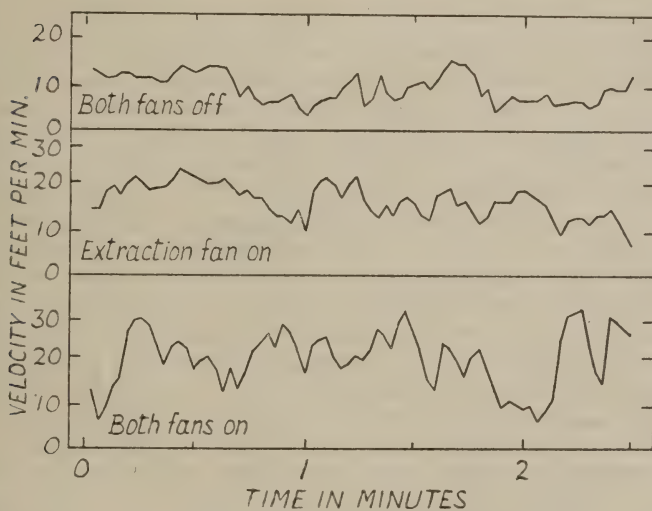


FIG. 5. Effect of plenum and extraction fans on oscillations of velocity.

considerable, as is indicated by Fig. 4. This is a composite curve made by averaging the results of eleven 10-minute observations in which a motor attached to the plenum ventilation system was turned on and off for $\frac{1}{2}$ and 1 min. intervals. It will be seen that the intermittency is fairly regular, though the individual records, of which a sample is reproduced above the composite curve, showed considerable irregularities. From considerations of space, only the first 7 minutes of the records are reproduced.

In one instance we were able to investigate the effect of plenum ventilation coupled with extraction. The room, 100 $\times$ 50 ft. in area,

and 30 ft. high, had sixteen gratings on each side, $8 \times 2\frac{3}{4}$ ft. in area, and 8 ft. above floor-level. Through them heated or cold air could be driven by a 5-ft. plenum fan, whilst the air could be extracted by another fan through a series of openings in the ridge of the roof. The air of the room was also heated by hot-water radiators under each plenum inlet. We made observations in a line at right angles to the radiators, and at a distance of 4, 14 and 25 ft. from them, half of the positions being opposite the radiators, and half in between them. Six observations were made (a) with plenum and extraction fans fully on, (b) with only the extraction fan on, and (c) with neither fan on. The results obtained were fairly concordant, and they showed a mean velocity of 18, 15, and 13 ft. per min. respectively under the three conditions, whilst the mean variation of the velocity was 30, 27, and 21 per cent. Hence the double system of ventilation appeared to give a better result, as regards variability of air current, than that observed in other rooms ventilated by a plenum system only, but it is impossible to speak definitely without making much more comprehensive investigations. A typical record of the oscillations of velocity observed at one spot is shown in Fig. 5.

7. LABORATORY EXPERIMENTS ON FAN VENTILATION.

In order to obtain further light on the production of air movement by mechanical ventilation, we made a number of experiments in a laboratory. The ventilating air current was produced by means of a 15-inch electric fan, which could be driven at any desired speed by the interposition of a rheostat in the circuit. This fan was placed in a draught chamber with a sliding door, 27×30 inches in area. The chamber was 26 inches deep, and was connected with the outside by a 6-inch pipe. The fan was kept revolving at a medium velocity, and as the door could be open or shut in less than a second, the air current to the room was turned on and off almost instantaneously. Most of the experiments were made in a small room 12×16 ft. in area, and 10 ft. high, and the hot-wire detector was placed (a) 5 ft. away from the fan in a line at right angles to its plane of revolution, (b) 14 ft. away, and slightly off this line, and (c) 16 ft. away from the fan, but in the opposite corner of the room, so that the air current had to rebound off two walls before reaching it, and traverse a distance of 24 ft. In order to reduce chance oscillations of air movement as much as possible, each experiment was made six times under similar conditions, and a mean composite curve constructed. From Fig. 6 it will be seen that when, during the first two minutes, the ventilation was shut off, the air currents in the room had a velocity of about 10 ft. per min., but when it was turned on their velocity speedily rose to about 200 ft. per min. at the spot 5 ft. from the fan. On shutting off the ventilation, the velocity fell in 10 seconds to about 30 ft. per min., but it did not reach its original level for $1\frac{3}{4}$ minutes. In the other two spots the fan caused an air velocity of about 55 and 33 ft. per min., but when the ventilation was shut off the velocity gradually subsided to normal at about the same rate as before, so it appears that the rebounding air currents were moving to about the same extent in all parts of the room.

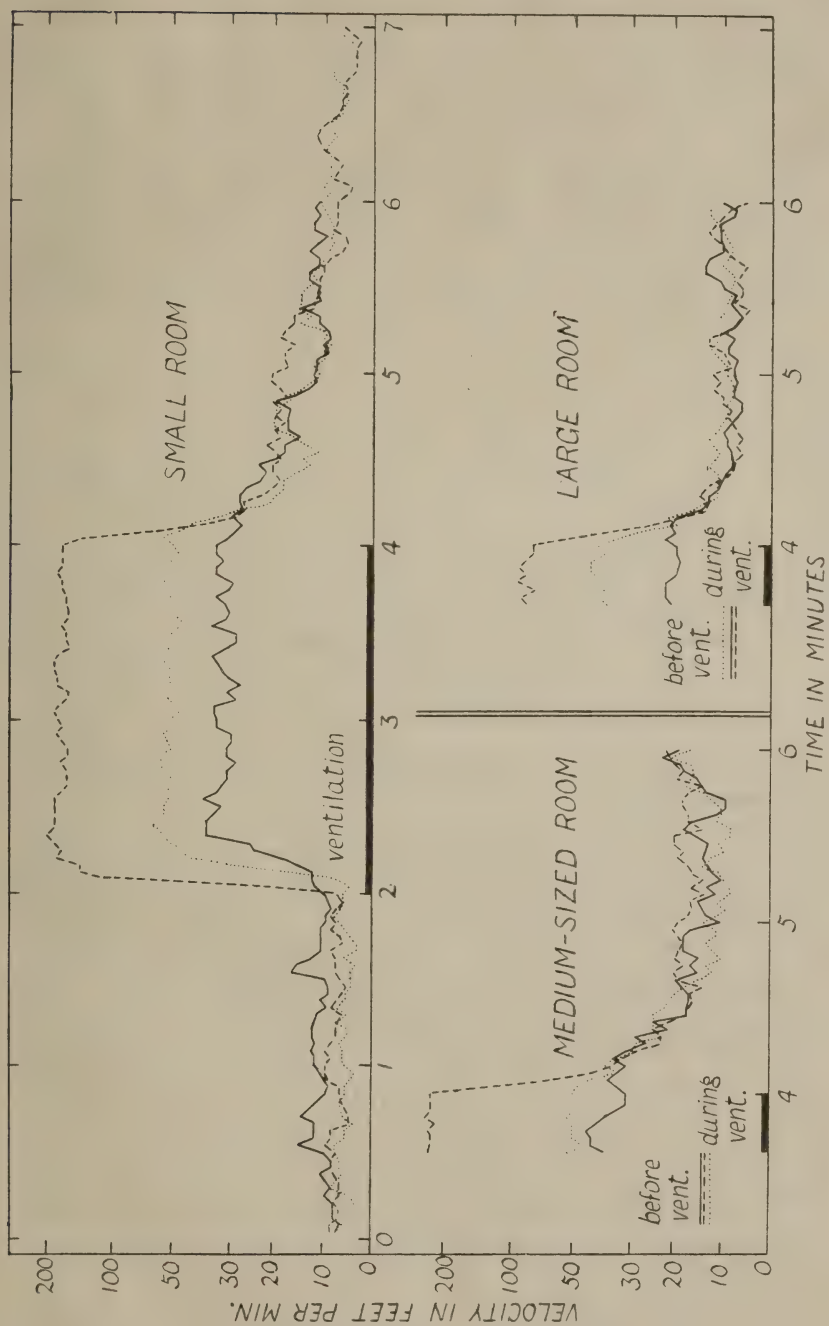


FIG. 6. Air currents induced at various distances from fan.

On repeating the observations in larger rooms, the rebound was found to be very much smaller. The second set of curves shown in Fig. 6 was obtained in a room 18×20 ft., and 10 ft. high, and they are the means of three sets of observations made (a) with the detector 6 ft. from the fan in a direct line, (b) 10 ft. from it in a direct line, and (c) 14 ft. away, and protected by a bench, so that the air had to rebound once from a wall and move 22 ft. before reaching the detector. The fan, which was revolving at maximum velocity, was placed in a cupboard with a door 2 ft. square. In order to save space, the first portion of the curves is omitted, though the average air velocity observed in the first two minutes (in the absence of ventilation) is indicated. The ventilating current, when turned on, caused similar velocities to those observed in the small room, but when it was turned

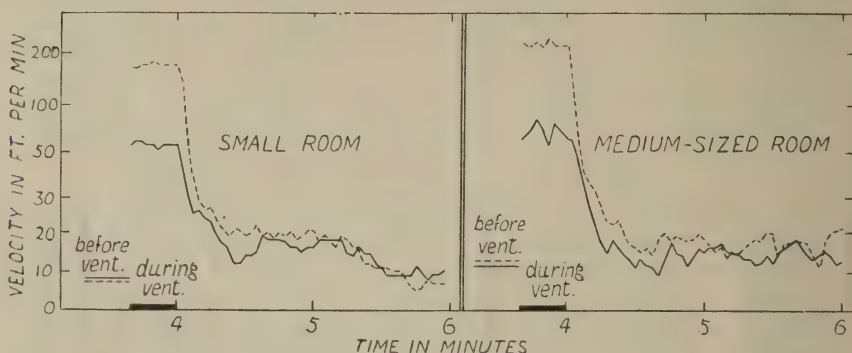


FIG. 7. Air currents induced by various velocities of fan.

off the velocity sank to normal in less than a minute at each of the spots investigated.

A third set of observations was made in a room 39×19 ft. in area, and 16 ft. high. The fan was placed in a draught chamber at one end, with a sliding door $2 \times 2\frac{1}{2}$ ft. in size. The detector was placed 3, 4, and 7 ft. off in a direct line with the fan, and even then it induced an air velocity of only 90 to 20 ft., though the maximum fan velocity was employed. If placed further away, or not in the direct line of the fan, it produced a scarcely measurable amount of air movement. This must have been due largely to the air no longer rebounding because of the large size of the room, for the third set of curves in Fig. 6 (the mean of 5 to 9 sets of observations in each case) show that on shutting off the ventilating current the velocity fell to normal in half a minute. Evidently the rebounds reinforce the air movement induced by the fan in proportion to their magnitude, for our observations show that, roughly speaking, the medium velocity fan used in the small room caused as much air movement as the rapid fan used in the medium-sized room, and a much greater velocity than the rapid fan used in the large room.

Other observations appeared to show that the force of the ventilating current has much less effect than the size of the room on the magnitude and duration of the rebounding currents. Thus in the curves recorded on the left side of Fig. 7, which were obtained

in the small room, the fan was damped down so as to cause an air velocity of about 55 ft. per min., at the spot 5 ft. away, instead of the previous 170 ft.; yet it will be seen that the rebound was only slightly reduced (mean of six observations). A similar experiment made in the medium-sized room gave a similar result, as can be gathered from the curves recorded on the right side of Fig. 7.

An example showing the effect of repeated intermittencies of ventilation, similar to those investigated in factories, is recorded in Fig. 8. The experiment was made in the small room, at the three spots previously referred to, and the curves reproduced are the means of six sets of observations in each case. The ventilation was turned on for three half-minutes, with a minute interval in between, and it will be seen that the effects produced each time were fairly consistent. There was a lag of about 5 seconds between the time the air current reached the second spot and the first spot, and another 5 seconds before it reached the third spot. On turning the ventilation off, the air velocity so quickly subsided at spots (a) and (b) that there was much oscillation of air movement. At spot (c), however, where the air current reached the detector after rebounding from two walls, the velocity attained was only about 37 ft. during the ventilation, and the subsidence from this velocity was rather slower than at the other spots. Consequently the oscillation of air movement was less, but the average velocity over the consecutive periods of ventilation and non-ventilation was maintained at a distinctly higher level than that calculated from the pre-ventilation and the ventilation velocities. That is to say, intermittent ventilation in a small room, owing to the magnitude and duration of the rebounding air currents, does quite appreciably raise the mean air velocity above the theoretical as well as causing oscillations of velocity, and thereby it must increase the sensation of air movement experienced.

It might be thought that, as the workrooms investigated were considerably larger even than the largest room utilized in the present experiments, the effects of rebound would be insignificant. This does not necessarily follow, for there were a large number of plenum ducts in the workrooms, each of them discharging an air current which was found to range in velocity from 1,170 to 3,400 ft. per minute. Control observations indicated that at certain spots these rapid currents did rebound with considerable velocity from the factory walls.

We wish to express our indebtedness to Dr. Greenwood and Miss Newbold (of the Statistical Department, M.R.C.) for their advice, and for assistance in working out the correlation ratios.

8. SUMMARY.

The relationship between the sensations of air movement experienced and the cooling power of the kata-thermometer was investigated empirically in a large number of factories. The investigators recorded their sensations (according as they considered the air to be 'very stagnant', 'very fresh', or one of the other seven intermediate classes agreed on), and then determined the cooling power of the air and measured its oscillations of velocity and temperature. Some 229 observations were made in summer time, and 203 in winter, and



FIG. 8. Effect of intermittent fan ventilation.

the mean results show that to produce a given sensation of air movement in winter required a cooling power about one unit higher than that required in summer. This was due to acclimatization, and the mean cooling power (in relation to a given sensation) was found to change gradually from month to month as the mean temperature changed.

It was found that the various degrees of 'stagnancy' experienced in factory air were due entirely to differences in the air temperature, whilst the various degrees of 'freshness' were due chiefly to differences in air velocity. The cooling power of the kata-thermometer combines these two variables better than any other known measure, and the correlation ratio of cooling power on air sensation was found to be .703 in summer, and .790 in winter. However, a considerable allowance has to be made for acclimatization; e. g. if a cooling power of 6 is reasonable during mild weather, one of 5 may be equally reasonable during hot weather, and one of 7 during cold weather.

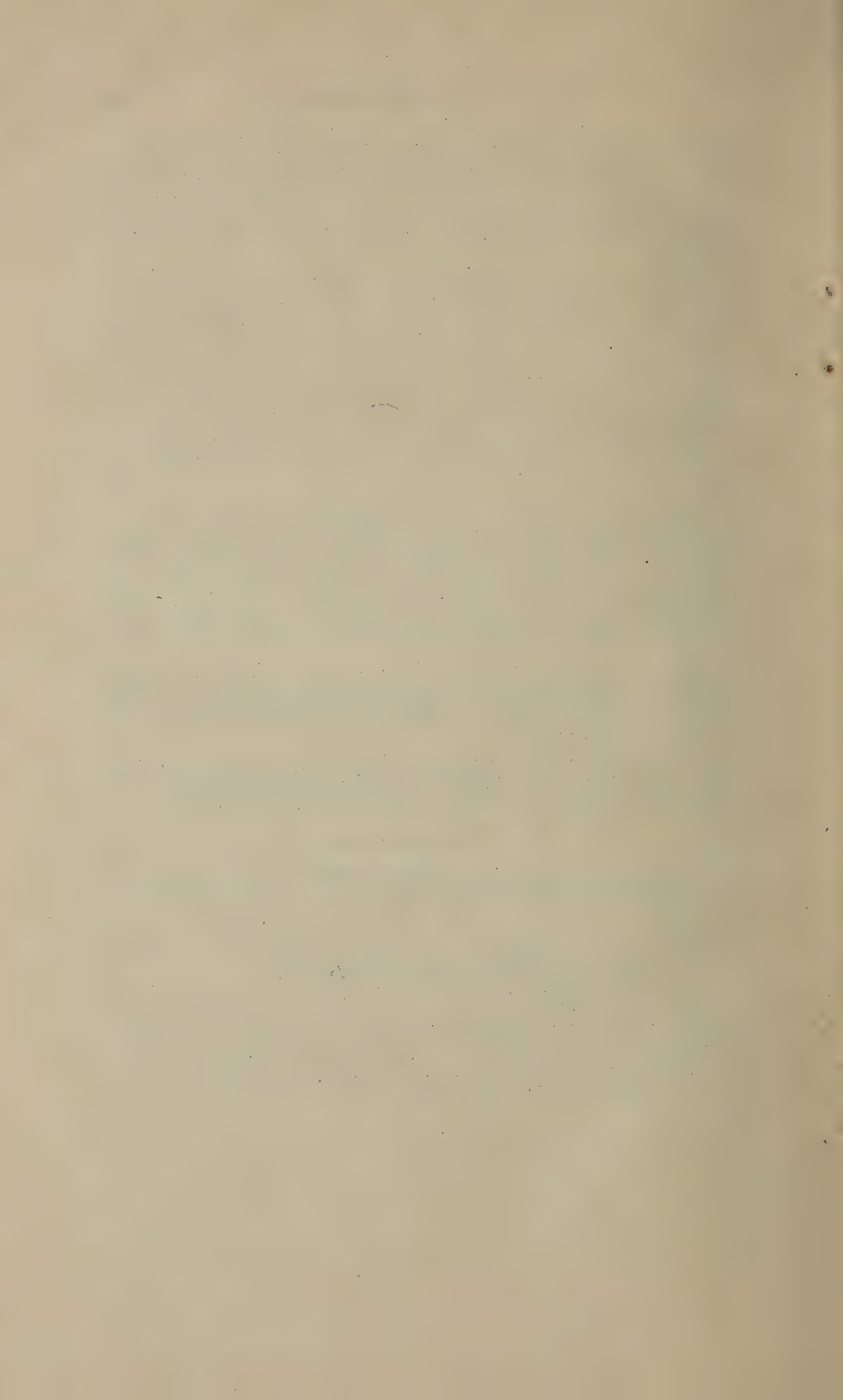
The sensation of air movement experienced is increased to a moderate extent by increasing the oscillations of air velocity. These oscillations were estimated in terms of the percentage mean variation, and the correlation ratio of mean variation on air sensation was .365 in summer, and .418 in winter. No clear proof was obtained that oscillations of temperature increase the sensation of air movement.

The air velocity is only slightly increased by turning on the plenum ventilation in factories, whilst the oscillations in velocity are slightly diminished. Intermittent ventilation considerably increases the oscillations in velocity.

Air currents (induced by a fan) continue to rebound from the walls of a room for as long as $1\frac{3}{4}$ minutes after shutting off the ventilation if the room is small, but in large rooms they are much slighter.

REFERENCES.

- HILL, LEONARD (1919): The Science of Ventilation and Open-Air Treatment. *Medical Research Council, Special Report Series*, No. 32.
 — (1920): The Science of Ventilation and Open-Air Treatment, Part II. *Ibid.*, No. 52.
 HOUGHTEN, F. C., and YAGLOGLU, C. P. (1923): Determination of the Comfort Zone. *J. Am. Soc. Heating and Vent. Eng., Reports*, p. 29.
 — — — Determining equal Comfort Lines. *Ibid.*, 29, 165.
 — — — (1924): Cooling Effect on Human Beings produced by various Air Velocities. *Ibid.*, 30, 169.
 VERNON, H. M. (1923): The Index of Comfort at High Atmospheric Temperatures. *Medical Research Council, Special Report Series*, No. 73, 116.
 YAGLOGLU, C. P., and MILLER, W. E. (1924): Effective Temperature applied to Industrial Ventilation Problems. *J. Am. Soc. Heating and Vent. Eng.*, 30, 515.
 — — — (1925): Effective Temperature with Clothing. *Ibid.*, 31, 59.



PART IV. THE INFLUENCE OF TEMPERATURE, AIR VELOCITY, AND CLOTHING ON THE RATE OF COOLING OF THE HUMAN BODY

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1. INTRODUCTION.

WE have seen that the cooling power of the dry kata-thermometer, after being corrected for acclimatization, affords a good measure of the cooling power of the air in so far as it affects our sensations of air movement. For individuals engaged in sedentary occupations and on light work at reasonable temperatures this is all that is required, but for men engaged in heavy occupations or working under very hot conditions the kata is not nearly so good an index, though information is gradually being collected which suggests that the *wet* kata-thermometer may prove a fair index. The performance of hot and heavy work causes a considerable rise of body temperature, which in turn provokes a vigorous perspiration, and the men employed desire such conditions of air temperature and velocity, and of clothing, as will induce the maximum degree of cooling of the body. It is important to ascertain, therefore, the relative degrees of importance attaching to the three factors of air temperature, air velocity and clothing in the cooling of the human body, with a view to taking the best remedial measures whenever possible. The subject is a very difficult and complex one, but it was thought that useful information could be obtained by direct observations on the rate of cooling of the human body under various well-defined conditions.

2. THE METHOD OF EXPERIMENT.

The method of experiment adopted consisted in warming up the body to a convenient height by means of step climbing, and subsequently determining its rate of cooling. All the observations to be described were made by the writer on himself and at his home, where the conditions of experiment could be kept very steady.

Breakfast was taken at 8 a.m., the temperature observations were begun at 9, and continued till about 1 p.m. The room in which they were made was not artificially warmed, but as observations were carried on during every month of the year from May to December, a sufficient range of air temperature was obtained (37° to 78° F.). The windows of the room were closed and partly shuttered, and thereby the amount of air movement in the 'still air' experiments, and the diurnal range of temperature, were kept very low.

Rectal and mouth temperatures were taken by means of half-minute thermometers at intervals of 10 to 15 minutes, the thermometers being kept *in situ* for three minutes. When step climbing, the body was raised and lowered 33 feet per minute, and the climbing was continued till the rectal temperature rose to something between

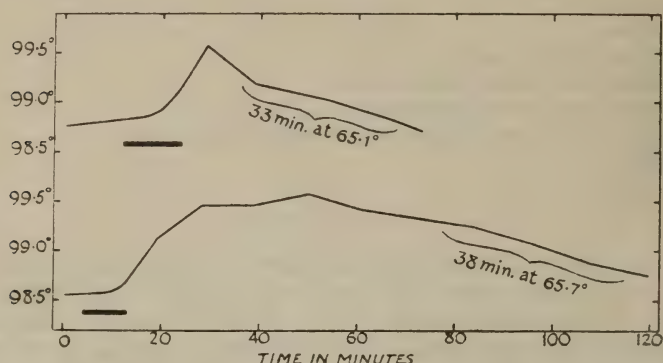


FIG. 1. Effect of acclimatization on rise and fall of body temperature after exercise.

99.5° and 99.9° F. Higher temperatures than this must be avoided, as they are apt to provoke sweating, and upset the result. Cooling was allowed to continue till the rectal temperature had fallen slightly below 98.80° , and thereby the actual cooling time of the body through the temperature range of 99.30° to 98.80° could be determined in minutes. This range was found to be the most suitable and convenient one in my own case, but it would not necessarily be the best for other individuals. The half-degree of temperature seems a small interval, but if it be extended it is apt to pass into the sweating stage in one direction, and the shivering stage in the other.

A possible source of error in the determination of cooling times lies in the diurnal variations of body temperature, for the normal and natural rise tends to get less and less as the morning wears on, and therefore a given loss of heat from the body would produce a different fall of temperature at different times. However, it will be shown in a subsequent section that under the conditions of experiment adopted my body temperature kept nearly steady throughout the morning. I generally determined the shorter cooling times twice in the course of the morning, viz. at about 10–11 a.m., and 12–1 p.m., whilst the longer cooling times were determined only once, generally at about 11 a.m. to 12.30 p.m.

Another source of error depends on the vaso-motor system. Cooling observations were made in still air and in moving air, and with various amounts of clothing, and inevitably the degree of vaso-constriction of the skin vessels would vary under these conditions. Moreover, it is greatly affected by *acclimatization*. In the earlier experiments my rectal temperature continued to rise only for a few minutes after cessation of the step climbing, and then fell gradually and steadily. Later on, however, the interval between cessation of exercise and temperature culmination got longer and longer, till after four months it reached an average value of 42 minutes. In Fig. 1 are shown two experiments, both made in still air at 65° F., and without clothing. In the first one the body temperature began to fall 5 minutes after the cessation of step climbing, and in the second one, made 17 days later, it did not fall till 37 minutes after the step climbing. The longer interval was presumably owing to the vaso-motor system more effectually constricting the skin blood-vessels, and preventing the cooled blood from reaching the internal organs. In the pair of experiments recorded in the third curve of Fig. 2 the intervals amounted to 43 and 34 minutes.

On splitting up all the observations made into convenient groups, and averaging, the following results were obtained :

<i>Date of observations.</i>	<i>Number of observations.</i>	<i>Minutes to culmination.</i>
May 25 to July 5 . . .	19	10
July 6 to July 31 . . .	22	28
Aug. 6 to Aug. 31 . . .	12	36
Sept. 17 to Sept. 26 . . .	12	37
Oct. 3 to Oct. 26 . . .	15	42
Nov. 5 to Nov. 21 . . .	16	42
Nov. 22 to Dec. 15 . . .	17	42

It will be seen that for the first six weeks the interval between the cessation of work and the temperature culmination averaged only 10 minutes. In the next month it was 28 minutes, and after two months more it reached a steady value of 42 minutes.

It might be thought that this acclimatization factor would prevent any valid comparison being made between the cooling times observed in the earlier and the later observations, but an analysis of the data obtained failed to show any consistent difference between them. Presumably the increasing vaso-constriction simply delayed the passage of the cooled blood from the skin surface to the internal organs for a certain number of minutes, and the rate of transference, once it was established, was scarcely altered.

3. THE COOLING RATE OF THE UNCLOTHED BODY.

A large number of observations were made on the rate of cooling of the unclothed body, as such a body is more directly comparable to the kata-thermometer than the clothed body, and should afford a more reliable basis for comparison. As a rule, observations were made in still air and in moving air on alternate days. The air movement was produced by a 15-inch electric fan, placed 16 feet away from where I stood. It was always run at the middle speed, and created

an air current of about 100 feet per minute. The velocity was determined by means of the kata-thermometer at intervals throughout the cooling observations, and small adjustments of velocity were effected by putting wire paper-fasteners on the vanes. The fan had an oscillating arrangement, and in the hope of rendering its cooling effects more pleasant and natural, it was made to oscillate through an angle of about 20° , each single oscillation taking 6 seconds.

The course of a typical morning's work is shown in the upper pair of curves of Fig. 2. After taking the rectal and mouth temperatures at 9.5 a.m., I step-climbed for 6 minutes, as I judged by my bodily sensations that this period was sufficient for the purpose.

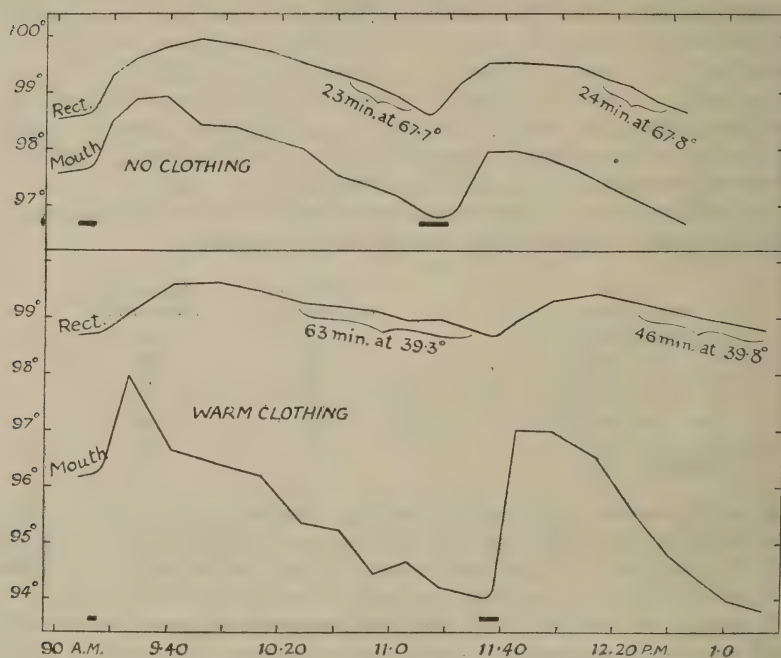


FIG. 2. Rate of fall of rectal and mouth temperature when in moving air.

It sent up my rectal temperature from 98.55° to 99.94° , and it was not until 10.44 that my temperature had fallen to the upper specified limit of 99.30° . At 11.7 it had sunk to the lower specified limit of 98.80° , so the cooling time amounted to 23 minutes. A further bout of step climbing was then undertaken for 10 minutes. This sent up my temperature to 99.56° , and during the subsequent fall a cooling time of 24 minutes was observed. It will be seen from the second curve that the variations of mouth temperature ran more or less parallel with those of rectal temperature, but usually they differed considerably, as is well shown by the lower pair of curves in Fig. 2.

Altogether 22 observations were made in moving air, and 14 in still air. The cooling times observed, for the half-degree of temperature, are recorded in Table I. They are classified in convenient groups, according to the mean temperature of the air during the

TABLE I. Times taken by the body to cool from 99.3° to 98.8°.

Clothing worn.	In moving air.		In still air.		Fall in temp. of mouth/rect.	
	Mean temp.	Cooling time in minutes.	Mean air vel.	Mean temp.	Cooling time in minutes.	
None	76.2°	56, 96, 78, 85	117	71.9°	75, 60	1.0, 1.2
	73.3°	36, 44, 48, 38	119	68.4°	49, 46, 37	0.8, 1.0, 1.0
	69.9°	29, 30, 29, 32, 23, 50	108	63.8°	38, 33, 47, 38, 33	1.1
	65.2°	23, 24, 26, 25, 26, 36, 23, 37	102	54.4°	30, 30, 28, 20	1.0, 1.6, 1.3, 1.2
(1) Vest and trousers	67.7°	87, 74	114	63.5°	84, 85, 66, 95, 72	1.2, 1.1, 1.8, 2.1, 2.1
	65.5°	86, 52, 44, 36	102	58.0°	59, 38, 37	2.0, 1.6, 1.6
	58.9°	36, 28, 28, 33, 37	116	55.0°	33, 51, 22	1.7
	55.4°	28, 30	93	52.9°	30, 33, 32	1.7
(2) Light clothing	59.5°	103, 66, 57, 75, 100	117	56.7°	98, 37, 108	2.0, 2.0, 2.9
	54.8°	45, 70, 38, 24, 35, 29, 51	104	52.1°	34, 50, 39, 44, 32, 38	1.7, 2.7, 1.4, 2.0, 1.5
	50.1°	22, 41, 37	85	46.8°	29, 35, 34	1.7, 3.8, 2.4
	49.3°	123, 69, 98	87	46.8°	98, 113, 38	3.0, 2.2, 2.3
(3) Warm clothing	44.9°	69, 30, 46, 44, 80, 68	87	44.3°	39, 46, 116	2.2, 1.9, 3.9
	38.9°	46, 63, 31	81	38.7°	71, 42, 22, 57, 60	2.7, 3.1, 2.9, 2.9, 3.0

cooling time. It will be seen that, for instance, the cooling times observed at a mean moving-air temperature of 76.2° amounted to 56, 96, 78, and 85 minutes on four occasions, or to 78.7 minutes on an average. The four cooling times observed at 73.3° are less divergent, as they vary only from 36 to 48 minutes, whilst those observed at the lower temperatures are for the most part more consistent still. The observations made in still air are likewise fairly consistent.

The average air velocity observed in the moving air experiments is recorded in the Table, and it will be seen that it ranged from 102 to 119 feet per minute, whilst it averaged 111 feet for the whole

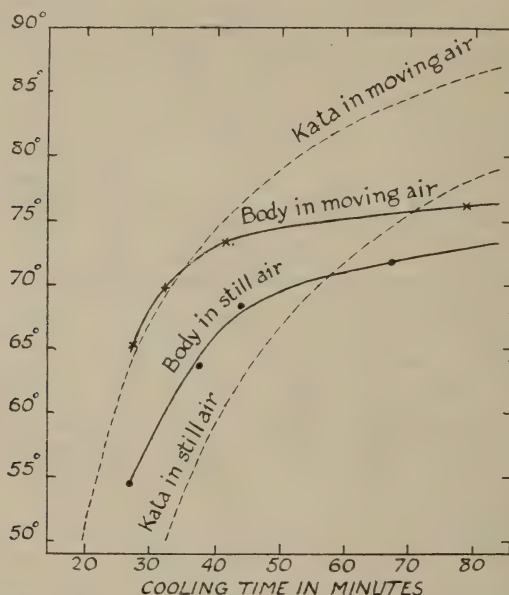


FIG. 3. Cooling rates of unclothed body and of kata-thermometer.

series. In the still-air experiments it varied only from 10 to 14 feet, so it is not recorded.

The mean cooling times are plotted out in Fig. 3, and it will be seen that they agree fairly well with the smoothed curves drawn through them. In order to obtain a direct comparison with the cooling of the kata-thermometer, I have calculated the cooling powers of a kata with a factor of 500, and have multiplied the ascertained times by 30 (and have then divided by 60, in order to convert into minutes). I have assumed that the still air had a velocity of 10 ft. per min., and the moving air one of 100 ft. It will be seen that whilst the lower portions of the cooling curves of my body agree fairly well with the corresponding kata-thermometer curves, the upper portions show no sort of agreement. With rise of air temperature, the cooling times of my body increased relatively much more rapidly than the cooling times of the kata, and the reason of this is simple. The kata curves are calculated on the assumption that in air at 97.7° F. (36.5° C.), the kata ceases to cool and remains

in equilibrium, whilst at lower temperatures its rate of cooling is proportional to the difference of air temperature and equilibrium temperature. The human body, however, is constantly producing a large amount of heat, and on this account its equilibrium temperature is considerably lower than 97.7° (if the additional body-cooling mechanism of sweating be excluded). It can, in fact, be calculated to be about 81° in still air. From the still-air curve in Fig. 3 I have read off the cooling times at temperatures between 62° and 72° , and it will be seen from the Table that they range from 34 to 69 minutes. If each cooling time be multiplied by the corresponding difference between air temperature and 81° , we get a series

<i>Air temperature.</i>	<i>Difference from 81°.</i>	<i>Cooling time in minutes.</i>	<i>Difference $\times$ cooling time.</i>
72°	9	69	621
70°	11	52	572
68°	13	45	585
66°	15	40	600
64°	17	37	629
62°	19	34	646

of values which are nearly constant, as can be seen from the Table. That is to say, the equilibrium temperature of my body is 81° , just as that of the kata is 97.7° . When a similar calculation is performed for the moving-air data, the equilibrium temperature works out at 83° , or 2° higher than in still air. This increase is to be expected, as moving air sweeps aside the convection currents of warm air which ordinarily surround the body, and thereby increases its rate of heat loss.

It will be realized that these estimates of equilibrium temperatures of the human body are rough, but they are sufficiently accurate to indicate that the naked human body, owing to its internal heat production, cannot be closely comparable to the kata-thermometer. Again, it may be thought that these estimates, being indirect, are liable to some unknown and considerable sources of error, and that the only satisfactory method of substantiating them would be to remain for some hours in still air at 81° , or in moving air at 83° , and show that the body temperature kept steady. I had no facilities for performing these particular experiments, but corresponding experiments on the clothed human body are described in the next section.

4. THE COOLING RATE OF THE CLOTHED BODY.

Three series of observations on the cooling rate of the clothed human body were made. In series (1) I wore a thin woollen vest with short sleeves, flannel trousers, thin socks and boots. In series (2) I wore in addition a flannel shirt of medium thickness, fastened at the neck and wrists, and thin woollen pants, whilst in series (3) I wore winter clothing, consisting of a thick tweed coat and waistcoat, thick woollen vest with long sleeves, thick woollen pants, thick socks, the usual flannel trousers and shirt, boots, and a linen collar.

It will be realized that in series (1) my body was, for the most

part, covered with a single layer of cloth. In (2) it was covered with two layers, and in (3) with two to four thicker layers.

The cooling times observed are recorded in Table I. In series (1) 13 observations were made in moving air, and 14 in still air. The observations are for the most part fairly consistent, but those obtained in series (2), when what may be described as 'light clothing' was worn, are less so. Most inconsistent of all were the warm clothing observations (series 3), but they owe part of their irregularity to a rather sudden acclimatization. All the observations were made during November and December, and in the middle of them, from Nov. 26 to Nov. 29, the air temperature was at 37° – 39° . These very unpleasant temperature conditions acclimatized me considerably, so that the rate of cooling observed on subsequent occasions was distinctly slower than it had been on previous occasions. This is shown strikingly by the following pairs of observations, carried out at the same air temperatures, but before and after the acclimatization :

{	On Nov. 22–24, at 43.8° (42.1° – 44.6°), cooling time in still air was	}
	46, 39, 71 = 52.0 min.	
{	On Dec. 5, at 43.6° , cooling time in still air was 116.0 min.	}
{	On Nov. 23, at 43.7° (42.9° – 44.4°), cooling time in moving air was	}
	68, 44 = 56.0 min.	
{	On Dec. 6, at 43.7° , cooling time in moving air was 80.0 min.	}

Other observations showed a somewhat smaller effect, but they are not quoted, as the air temperatures did not correspond sufficiently closely.

This phenomenon of acclimatization must have been operating to a greater or less extent during the whole of the observations, though for reasons stated it was specially evident in this particular series. Even if the observations had been made in a room artificially warmed to the desired temperature, and the amount of clothing worn had been changed from day to day, the body would still have undergone acclimatization during non-experimental hours (cf. Part III of this Report). It is probable, in fact, that the system adopted of making observations in an unheated room, and with clothing appropriate to the particular temperature conditions at the time, is the best that could have been chosen. The acclimatization effect, though it induces some irregularity in the results, does not invalidate them. It might be maintained that, as the warm clothing experiments were so irregular and so specially affected by acclimatization, I ought to have made more of them; but they were too unpleasant. My mouth temperature often fell below 94° , and the moving-air experiments gave me rheumatism in the neck, which persisted for months. This was in spite of the fact that in all moving-air experiments I turned round slowly about once a minute, so as to expose both front and back to the draught.

The smoothed curves of the various series of cooling times plotted in Fig. 4 show a considerable resemblance in slope, and this resemblance affords strong evidence of their substantial correctness. It will be seen, however, that whilst the moving-air and still-air components of the two upper pairs of curves are some distance

apart, those of the two lower pairs are near together. This indicates that the effect of moving air on the cooling rate was considerably greater in the 'no clothing' and the 'vest and trousers' series than

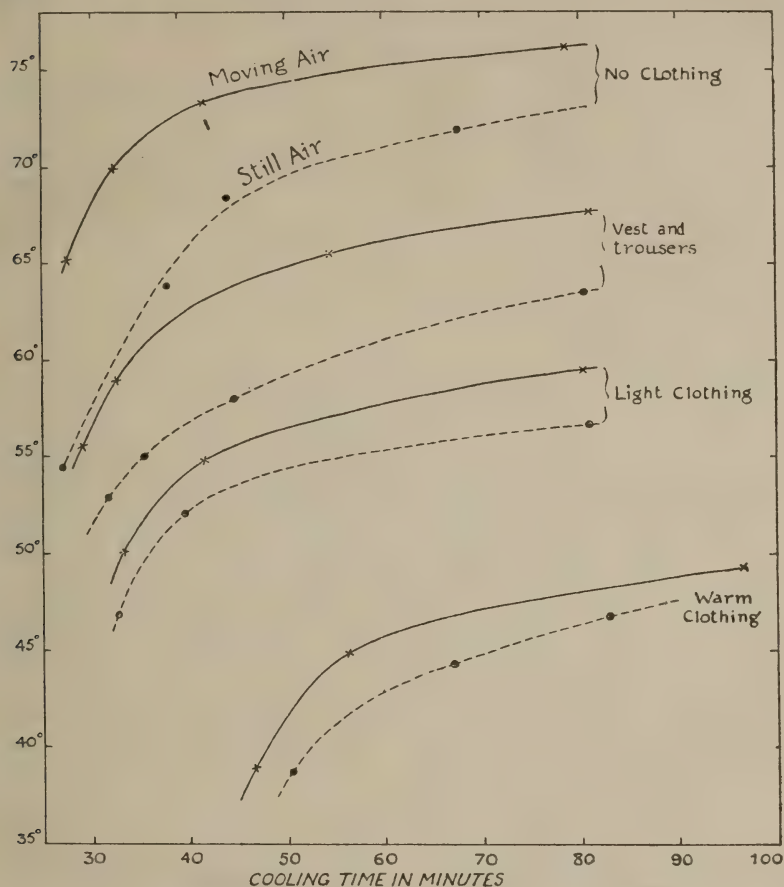


FIG. 4. Rate of cooling in relation to air temperatures and clothing.

in the other two series. A calculation of the equilibrium temperatures by the method previously indicated gave the following values :

	Equilibrium temperature in		Temperature equivalent of moving air.
	moving air.	still air.	
No clothing	83°	81°	2°
(1) Vest and trousers	75°	71°	4°
(2) Light clothing	67°	65°	2°
(3) Warm clothing	60°	59°	1°

These data show that in the lightly clothed and warmly clothed body the moving air caused an effect corresponding to a temperature difference of only 1° or 2°, whilst in the unclothed body and the body clothed in vest and trousers it caused one corresponding to

a temperature difference of 2° to 4° . These calculated temperatures are only approximations, but they are quite sufficient to prove that the cooling effect of the moving air was very small. They likewise prove, when taken in conjunction with the actual curves shown in Fig. 4, that the clothed body is less affected than the unclothed or very lightly clothed body.

In contrast with the very small effect of moving air, that of clothing is considerable. We see that the warmly clothed body remained in temperature equilibrium at 59° – 60° , or 22° – 23° lower than that required to maintain equilibrium in the unclothed body. We may conclude, therefore, that as a direct physical agent, and apart from its influence on our sensations, variations of air movement play a very much smaller rôle than differences of temperature and of clothing. The velocity of air movement observed in factories is usually under 40 ft. per min., and seldom exceeds 100 ft. per min., so the *direct* cooling effect of the moving air is usually insignificant.

Though these data indicate that air movement had comparatively little effect on the cooling of the human body under the particular conditions of experiment, it does not follow that its influence is always small. When the body is wet from perspiration it is much more sensitive to air movement. For instance, a 100 ft. air current, as compared with still air, will cause about twice as much increase in the wet kata cooling power as in the dry kata cooling power. A miner hewing coal at the face in a deep pit is usually bathed in perspiration, and wears few if any clothes, so he would experience a physical cooling effect from a 100 ft. air current about twice as great as that indicated by the upper curves in Fig. 4.

It can be seen from Table I that in the moving-air observations made at the lower air temperatures the velocity of the air was distinctly under 100 ft. per min. This was owing to the fact that, at the time the observations were made, the temperature corrections described in Part II of this Report had not been ascertained, and the air velocities employed were kept at about 100 ft. per min., as calculated on the uncorrected basis. However, the error introduced is not large, in comparison with the effects of temperature and clothing.

The wet-bulb temperatures are not recorded in the above observations, but the humidity was that usually experienced in our climate, and amounted to about 50 per cent. saturation at 70° , 60 per cent. at 60° , and 70 per cent. at 50° .

It is desirable that a direct proof be adduced of the approximate correctness of the equilibrium temperatures above recorded. Such a proof was obtained by making a series of 'light clothing' observations in still air. It is important to record the mouth temperature as well as the rectal temperature because it is more sensitive, and more quickly indicates any tendency to a fall of body temperature.

The upper pair of curves in Fig. 5 show the mean rectal and mouth temperatures observed on seven mornings when I was undoubtedly clothed sufficiently to maintain my body temperature. I was standing all the time, engaged in reading and writing, and it will be seen that my temperature rose over 1° F. between 9 and

11 a.m., after which it kept nearly constant. These curves serve as a standard, but in comparison with them I found that on the mornings when I was making experiments my body temperature reached a steady level much earlier (cf. curves I and III, Fig. 5), as I had to walk about for a few minutes when making the necessary preparations. The first of the four pairs of 'light clothing' curves show that at an air temperature gradually rising from 64° to 66° the rectal temperature kept nearly steady, though the mouth tem-

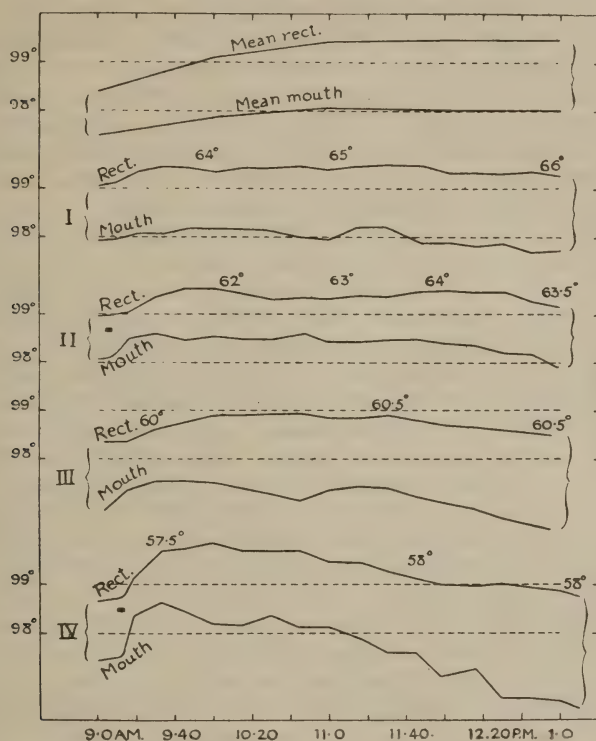


FIG. 5. Influence of air temperature on temperature of body (lightly clothed).

perature fell off 0.3° . In the second pair the body temperature was driven up at the start by $2\frac{1}{2}$ minutes' step climbing, and in air at 62° to 64° the rectal temperature remained steady till 12.30 p.m., and then began to fall. The mouth temperature kept steady till 11.45, and then fell, so this series of observations, coupled with the previous one, shows that air temperatures of 63.5° to 66° are on the border line of temperature equilibrium. Hence they support the calculated equilibrium temperature of 65° previously recorded.

The third pair of curves were obtained at an air temperature of 60° . It will be seen that both rectal and mouth temperatures started low, and after a certain amount of diurnal rise, the rectal temperature showed a marked fall from 11.30 onwards. The mouth temperature started falling at 10.0 a.m., and fell rapidly after 11.30.

Hence an air temperature of 60° was obviously too low to maintain the body temperature. In the last pair of curves recorded, the body temperature was raised by a preliminary 4 minutes' step climbing, but owing to the air temperature being only 58° , it fell rapidly from 10.0 (or 9.30) onwards.

5. A COMPARISON OF MOUTH TEMPERATURE AND RECTAL TEMPERATURE.

It is well known that the mouth temperature is a less reliable index of body heat than the rectal temperature, but the extreme unreliability indicated by the present observations was unexpected. The low temperatures observed were not due to experimental error, as the thermometer bulb was always kept for over three minutes under the tongue, and in cold weather it was warmed previous to its insertion. Moreover, I was careful not to breathe through my mouth at any time, because of the cooling effect.

It will be seen in Fig. 2 that when step climbing was performed, the mouth temperature shot up more quickly than the rectal temperature, and after reaching its maximum, it began to fall 15 or 30 minutes earlier. The rate at which it fell, compared with the rectal temperature, is recorded on the right side of Table II. The ratios quoted relate to the whole range of temperature fall observed, and not to what happened during the half-degree of rectal fall. They show that the buccal fall was almost always more rapid than the rectal fall, but the ratios were greatly influenced by the conditions of experiment. The unclothed body in still air showed a mean ratio of 1.1, but in moving air, one of 1.4. The clothed body showed bigger and bigger ratios the greater the amount of clothing worn, for series (1), (2), and (3) gave mean ratios of 1.7, 2.2, and 2.7 in still air, and of 1.8, 2.5, and 3.7 in moving air. A sample of the kind of temperature variations observed when the warmly clad body remained in cold moving air is given in the lower half of Fig. 2. In the first half of the experiment the rectal temperature fell from 99.60° to 98.70° , or through 0.9° , whilst the mouth temperature fell from 97.95° to 94.05° , or 3.9° . Step climbing was then performed for 7 minutes, and at the same time the jaw muscles and tongue were exercised a little in order to stimulate a flow of blood to the mouth. The mouth temperature shot up to 97.0° , and then gradually fell to 93.8° , or through 3.2° , whilst the rectal temperature fell 0.7° .

The mouth temperature fell to about 94° in all of the warm clothing observations made in moving air, and to 95° in those made in still air. Accompanying the very marked cooling of the unprotected mouth and face, the unprotected hands likewise cooled considerably, and to a less extent, the protected feet. Evidently the cooling effect of the air was exerted chiefly on these peripheral structures, and owing to the slowness of the circulation, it was only transferred very gradually to the internal organs of the body. It follows, therefore, that the rectal temperature is not a true index of the mean body temperature, though it is doubtless a much better index than the mouth temperature.

It might be thought that the considerable differences of mouth

temperature from the rectal temperatures which formed the basis of the previously described cooling rates of the body are sufficient to invalidate them. It is true that they must have influenced them to some extent, but they would not influence the equilibrium temperatures. At such temperatures it is supposed that the body temperature is maintained at a steady level both in the rectum, mouth, and other structures, and the mouth curves recorded in Fig. 5 show that this was the case, roughly speaking. The differences in the variations of rectal temperature and mouth temperature tend to get less and less as the equilibrium temperature is approached, till finally they vanish, and this view is supported by the data recorded in Table I. It will be seen that, in each series of records, the ratios got smaller and smaller the nearer the approach of air temperature to the equilibrium temperature. For instance, in the no clothing (moving air) series, the ratios were 1.6, 1.5, 1.5, and 1.2 at the respective air temperatures of 65.2° , 69.9° , 73.3° , and 76.2° , whilst in the warm clothing (moving air) series, the ratios were 4.4, 3.7, and 2.9 at the respective air temperatures of 38.9° , 44.9° , and 49.3° .

6. SUMMARY.

The rate of cooling of the human body between 99.3° and 98.8° was determined after its temperature had been raised by step climbing. It was found that in the unclothed or very lightly clothed body an air current of 100 ft. per minute, as contrasted with still air, caused an extra cooling corresponding to a lowering of the air temperature by 2° to 4° , whilst in the warmly clothed body it corresponded to a lowering of only 1° .

The effect of clothing on the cooling rate of the body is considerable. Thus it was calculated that the unclothed body of the subject of experiment would remain in temperature equilibrium at an air temperature of 81° – 83° , whilst the warmly clad body would remain in equilibrium at 59° – 60° . Hence, in order to induce an actual cooling of the overheated body of a man engaged in hot and heavy work, it is of most importance to reduce the temperature, and next in importance to reduce the clothing, whilst an increase of air velocity has but little effect.

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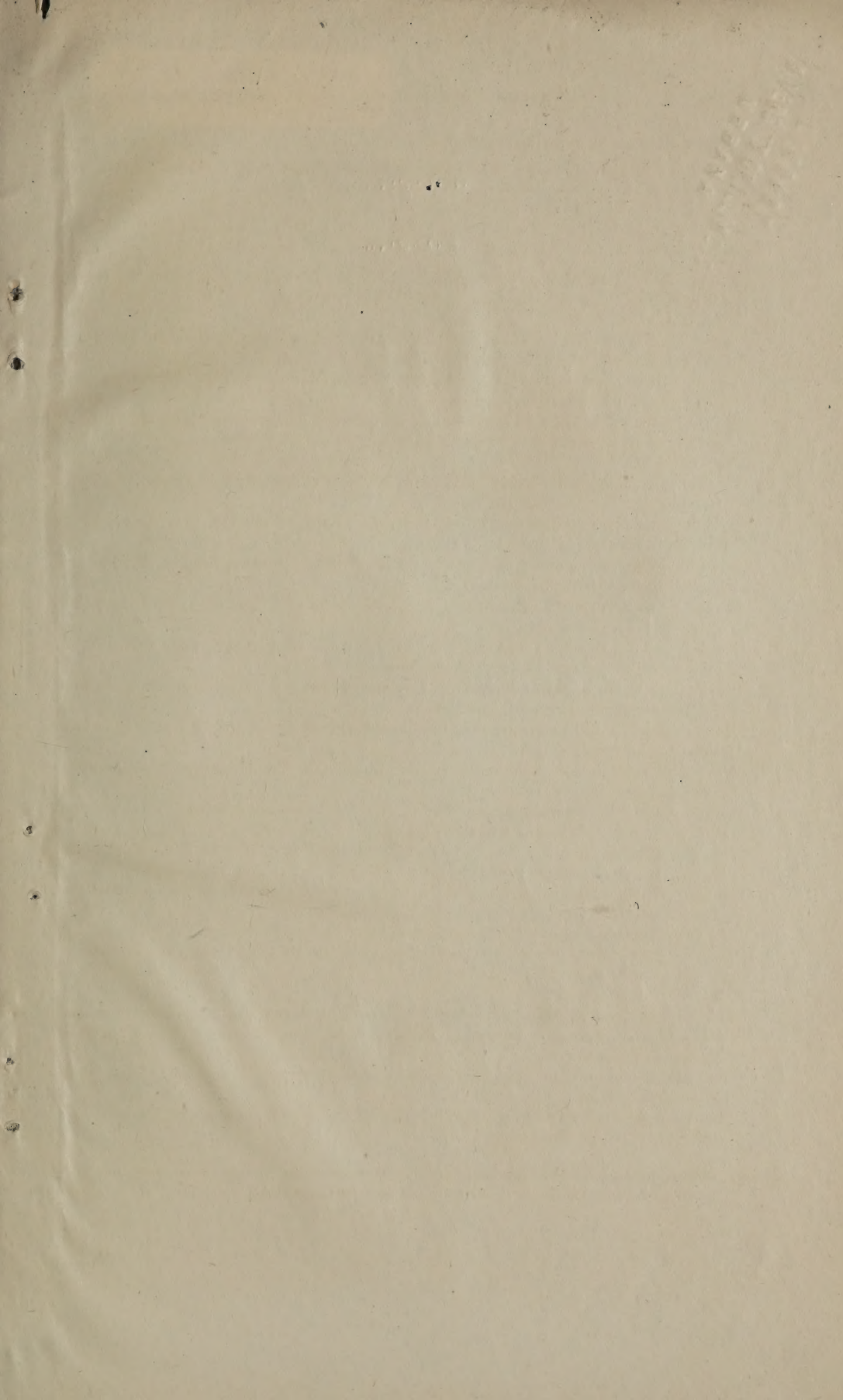
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